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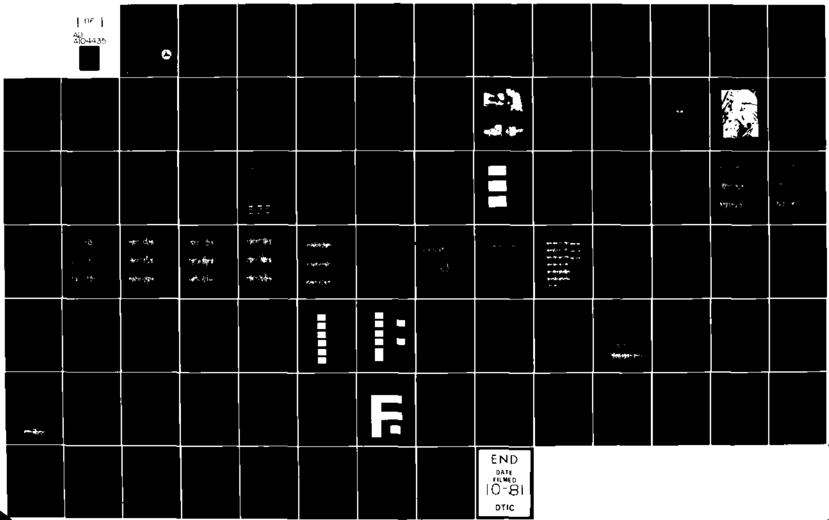

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DEVELOPMENT OF DIESEL ENGINE DIAGNOSTICS FOR U.S. COAST GUARD CUTTERS

JULY 1981

U.S. DEPARTMENT OF TRANSPORTATION

RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
TRANSPORTATION SYSTEMS CENTER • CAMBRIDGE MA 02142

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16. Abstract

This program involved an investigation of techniques to perform engine fault diagnosis on the large medium-speed diesel engines used as main propulsion power plants in medium- and high-endurance Coast Guard cutters. Two engine diagnostic parameters were defined and selected as the parameters of interest. They were (1) Instantaneous Crankshaft Angular Velocity (ICAV), which directly relates to the developed power contribution for each cylinder, (2) Dynamic Crankcase Pressure (PKD), which relates to the amount of gas leakage past the piston rings and into the crankcase. Prototype instrumentation was designed and developed to measure relative values of these parameters, and tests were conducted with several operating engines, some of them in Coast Guard cutters. Results of the development and test work were generally encouraging, but not definitive. This effort is therefore viewed as a step toward achieving the program goals. The report contains recommendations for further work.

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PREFACE

The Southwest Research Institute, under contract to the U.S. Department of Transportation, Transportation Systems Center (TSC), has developed a method for testing equipment for fault diagnosis of large marine diesel engines. Diagnostic techniques considered for prototype modification have been limited to those that can be applied without mechanical modification to in-service Coast Guard engines. These techniques will yield the widest range of useful diagnostic information for the least expenditure of time and money. The project monitor for TSC is R. Walter. F. Weidner is the project officer for the U.S. Coast Guard.

We wish to acknowledge the cooperation and assistance of personnel from the following ships and organizations in the pursuit of the objectives of this project:

U.S. Coast Guard Cutter COURAGEOUS (WMEC 622)

U.S. Coast Guard Cutter DURABLE (WMEC 628)

U.S. Naval Training Center, Great Lakes IL

ALCO Power Inc., G.E.C. Diesels, Ltd., Auburn NY

Fairbanks Morse Engine Division, Colt Industries, Inc., Beloit WI.

METRIC CONVERSION FACTORS

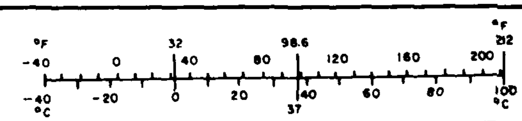
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. SUMMARY AND CONCLUSIONS

This report describes the work accomplished in Task 4, "Engine Diagnostics," of Contract DOT-TSC-920, Phase II. The primary objectives of this task were to examine candidate methods [1] of diesel engine fault location and diagnosis, to select promising methods for development, and to implement them in a cost-effective manner. To this end, two diagnostic parameters were chosen and techniques developed for their measurement. The first is Instantaneous Crankshaft Angular Velocity (ICAV) and the second is Dynamic Crankcase Pressure (PKD). In order to identify the position of a particular cylinder in the data readout record, an electrical signal was generated by a sensor attached to the desired cylinder's fuel injection line (generally No. 1 in the firing order). This data synchronization (SYNCH) signal gives an approximate indication of piston top dead center (TDC) since it coincides with injection for the target cylinder.

The introductory section of this report provides an overview of project objectives and a resume of germane background information. The selected diagnostic parameters and their measurement techniques are described next, followed by a description of laboratory prototype equipment development required to make the measurements. Test procedures, results, and conclusions from each of a series of tests on eight large diesel engines (including some in actual shipboard installations) are reported along with results from two smaller diesel engines at the Southwest Research Institute (SwRI). Finally, specific recommendations are made regarding future work with these fault diagnosis methods.

Conclusions to be drawn from the program are as follows:

> The ICAV waveforms of the various large diesel test engines responded in an often very subtle (and usually very complex) manner to induced power imbalance conditions in a single cylinder; however, inspection of the data demonstrates that ICAV changes from baseline <u>were evident</u> with induced power imbalance and for this reason the technique shows promise as a means of diagnosing and locating power imbalances caused by malfunctions in large diesel engines. The ICAV waveform changes for large engines are not so easily correlated with defects as they are for smaller engines; therefore, ICAV needs considerable equipment development and baseline engine data refinement to adequately define the design parameters of a practical diagnostic system. More particularly, ICAV test work during this project demonstrated that large diesel engines, because of their long crankshafts, operate (even at idle speeds) fairly near the first major crankshaft torsional resonance. This torsional resonance tends to obscure the crankshaft rotational contribution of

[1] Hambright, R.N., J.O. Storment, and C.D. Wood, <u>Selection of a Prototype Engine Monitor for Coast Guard Main Diesel Propulsion Engines</u>, Report No. DOT-TSC-USCG-79-3, Department of Transportation-U.S. Coast Guard, April 1979 (CG-D-131-76, NTIS AD A071712).

each individual cylinder (which is the information needed for ICAV diagnosis) and, therefore, ICAV data from large engines are more difficult to interpret than those from smaller engines (with fewer cylinders and shorter, stiffer crankshafts) which operate at rotational speeds well below this torsional resonance.

- One of the two smaller diesel engines tested produced good ICAV data as expected, but the other did not. These results are reported in Sections 5.8 and 5.9.

- Dynamic crankcase pressure (PKD) experiments during the course of this work were disappointing. The internal crankcase structure and compartmentalization of these large marine engines precluded obtaining usable results. Even though baseline PKD signals appear as expected in some cases, we must conclude from the data that a leakage defect would have to be of an extreme nature to be unambiguously detected by this method in its present state of development.

- Nominal TDC determination by means of simple instrumentation attached to the reference cylinder (usually No. 1 in the firing order) high-pressure fuel injection line was found to be quite practical. This technique of data synchronization (SYNCH) is a definite simplification over the usual magnetic pickup transducer method and proved adequate for all tests.

2. BACKGROUND AND INTRODUCTION

Southwest Research Institute (SwRI) began work in November 1974 on Contract DOT-TSC-920 for the Transportation Systems Center of the U.S. Department of Transportation and the U.S. Coast Guard Office of Research and Development. The initial part (Phase I) of this program involved an investigation of methods to reduce fuel consumption and exhaust emissions of large in-service diesel engines used in both locomotives and several classes of Coast Guard cutters. Phase I was completed in September 1975, with the publication of a report[2] that summarized the findings and conclusions and presented a list of recommendations as to the course that future (Phase II) efforts should take.

Part of the Phase I effort was to investigate and evaluate maintenance practices actually used with these large diesel engines. It subsequently developed that available information was not adequate to reach the goal of accurately determining the quantitative relationship between user maintenance practices and resultant effects on engine performance and emissions. As a positive result, however, this effort did produce valuable insight regarding the types of maintenance programs applied to these engines.

Specifically, the Coast Guard at that time employed an "as-required" maintenance program for the engine center section, which includes pistons, piston rings, cylinder liners, main and connecting rod bearings, and the crankshaft. Under this program standard instrumentation methods are used to determine the condition and performance of center section components. These methods include periodic analysis of the spectrochemical and physical properties of the lubricating oil and monitoring of operating parameters such as crankcase pressure, exhaust manifold pressure, intake manifold or air box pressure, and exhaust gas temperatures for individual cylinders. Values of these parameters, plus wear metal concentrations from lube oil analysis, are plotted as functions of engine operating time to obtain a time-based trend analysis of engine condition. Additionally, a final indicator of overall engine condition is provided by periodic full-power trials wherein the ability of the ship to meet certain performance criteria is determined. Individual cylinder values of exhaust temperature, firing pressure, and fuel pump rack setting are recorded during full-power operation and later analyzed to determine if the values are within the engine manufacturer's specified limits.

The "as-required" maintenance program, which is entirely conventional in nature, was in general found to be working well. There were, however, a

[2]Storment, J. O., C. D. Wood, and R. J. Mathis, A Study of Fuel Economy and Emission Reduction Methods for Marine and Locomotive Diesel Engines, Report No. DOT-TSC-OST-75-41, Department of Transportation-U.S. Coast Guard, September 1975 (CG-D-124-75, NTIS AD A009214).

number of cases reported that indicated there was room for improvement. For example, engines were found that required overhaul at intervals of 7,000 to 12,000 hours of operation (about one-half the usual time for the same engine models in other marine applications), and in at least two instances, there were engines that experienced severe, almost catastrophic deterioration of center section components without ever giving unambiguous indication of that fact in the measured values of performance parameters or lube oil wear metals concentration. It seemed likely to SwRI that if major engine problems could, in these cases, develop undetected, then minor (but potentially significant) problems also remained undetected. These minor problems not only have the potential of becoming progressively more serious, but can also cause fuel consumption and exhaust emissions (particularly smoke) to be above nominal levels.

It was therefore recommended that one goal of Phase II of the program should be to determine the parameters associated with performance of critical engine components and to develop both prototype instrumentation to monitor these parameters and the rationale needed to interpret the data. The information thus obtained would indicate when replacement or adjustment of a component was necessary, without the risk of either premature (hence, unnecessary) repair or, worse yet, component failure in service. It would then be possible to institute a maintenance program capable of producing maximum useful component life and maximum efficiency from the engine as a whole. This last item would automatically mean that fuel consumption and smoke opacity were maintained near optimum values.

Principal objectives of the Phase II engine fault diagnosis task in its final form may be summarized as follows:

- determine candidate parameters that are diagnostically significant for engine center section components,

- enumerate state-of-the-art measurement techniques for the candidate diagnostic parameters,

- select the most promising diagnostic parameters and perform the requisite instrumentation development work to implement their measurement with prototype hardware, and finally,

- use this hardware to examine induced effects in large diesel engines both in the laboratory and in actual shipboard installations.

This last objective was expanded considerably from the scope of work concepts of the original work plan, primarily because of the difficulty encountered in locating satisfactory test bed engines for experimental work. As will be shown in this report, this problem was not resolved completely even with the expenditure of much effort in shipboard testing.

3. DIAGNOSTIC PARAMETERS

3.1 Candidate Parameters and Selection Methods

The following compilation of engine operating parameters lists those things which may be measured to gauge the condition of a large diesel engine short of tearing it down. Some are commonly used, others are more exotic; but in any case, this list embraces all the candidate diagnostic parameters which were evaluated before selection of those that would be implemented during the course of project experimental work.

- engine speed
- engine output (shaft) torque
- horsepower
- main bearing temperature and oil pressure
- coolant into engine--temperature, pressure, and flow rate
- coolant out of engine--temperature, pressure, and flow rate
- oil sump temperature
- common (average) exhaust duct temperature and pressure
- common exhaust duct instantaneous temperature and pressure
- individual exhaust port average temperature and pressure
- individual exhaust port instantaneous temperature and pressure
- fuel inlet temperature, pressure, and flow rate
- return fuel temperature, pressure, and flow rate
- intake manifold or air box temperature and pressure
- air intercooler temperature and pressure
- turbocharger air temperature and pressure
- oil cooler inlet temperature and pressure
- turbocharger oil return temperature and pressure
- sea water injection temperature and pressure
- instantaneous crankshaft angular velocity (ICAV)
- cylinder pressure vs. time relationship (P-T)

- cylinder pressure vs. volume relationship (P-V)
- apparent rate of heat release of fuel in cylinder
- injection pump rack position
- crankcase blowby rate
- dynamic crankcase pressure (PKD)
- lubricating oil analysis for wear metals
- radioactive tracer measurement of wear particles.

Selection of the particular diagnostic parameters to be evaluated was guided by the following criteria, which were established by the Coast Guard, with consultation by SwRI:

- minimum (preferably no) mechanical modification required to the engine being diagnosed,
- diagnostic data immediately available and interpretable by usual ship's personnel,
- rugged and potentially portable test system hardware with lowest possible cost,
- hard-copy data display suitable for permanent record,
- maximum diagnostic information in each test procedure,
- minimum equipment calibration and maintenance required.

With these guidelines, ICAV and PKD were chosen as the most promising diagnostic techniques. Some means of identifying individual cylinders on the hard-copy readout is required for both ICAV and PKD; therefore, approximate TDC or data synchronization (SYNCH) was included for development.

3.2 Instantaneous Crankshaft Angular Velocity (ICAV)

Torsional vibrations have long been a principal concern of engineers engaged in the design of internal combustion engines. Various types of instrumentation have been developed and used through the years to measure torsional vibrations in an effort to assure that uncontrolled torsional resonances do not result in crankshaft breakage. Typical curves[3] depicting cylinder gas pressure versus crank angle in a four-cycle, one-cylinder engine, and the resultant torque on the crankshaft, are shown in Figure 3.1, with positive torque and pressure upward on the traces. If we add the torque contribution of additional cylinders in an idealized manner (see Figure 3.2, which illustrates these data for an eight-cylinder, four-stroke

[3]Taylor, C. F., The Internal Combustion Engine in Theory and Practice, Vol. 2, MIT Press, 1968, p. 270.

cycle engine), it can be seen that torque variation is reduced as we decrease angular spacing (i.e., increase frequency) of cylinder firings. However, even with firing impulses spaced 90° apart, as shown here, there is still a significant peak torque impulse delivered to the rotating mass by each firing event. Each impulse results in a momentary increase in angular velocity of the crankshaft.

The ICAV instrumentation described in this report is a practical means of measuring this departure from the average crankshaft rotational value. The magnitude of ICAV change is affected by cylinder firing pressure, engine load, the total inertial mass which the engine is rotating (flywheel, gearbox, etc.), friction of the rotating components, and anything else that either adds power to or removes power from the crankshaft. So long as each firing event's positive torque contribution is uniform, negative torque or load remains constant, and if there are no other inputs to the crankshaft, then the accelerations and decelerations of the rotating mass will be of uniform magnitude. At this point we must stress that torsional resonances, which both remove and then return power (minus losses) to the crankshaft, are not yet being considered. (An analogy may be helpful here: in electrical terms, the engine load is purely resistive, with no reactive component.) If we measure and accurately record the instantaneous crankshaft angular velocity (ICAV), we can directly observe and compare each cylinder's power contribution, and it should then be possible in practice to detect and localize a defect which causes power imbalance among the individual cylinders. This has indeed been found to be the case in previous diagnostic work on small diesel engines at SwRI.

As noted earlier, if the firing events move closer together in angular displacement, as when an engine has more cylinders or is of two-stroke cycle design, the ICAV variation becomes less pronounced because the positive torque inputs begin to overlap more, and the average torque and peak torque approach the same value. In addition, the inertia of an engine's rotating mass is specifically sized during design to reduce changes in ICAV to some desired (low) value of a particular constant, K, depending on the engine's intended type of service[4]. It is thus advantageous to load an engine undergoing diagnosis by ICAV to a mild "lugging" condition in order to reduce the inertial or flywheel effect. This simplifies diagnosis since the influence of each firing event becomes more pronounced in the ICAV record.

Precise measurement of torsional vibration magnitude, which when excessive can cause rough engine operation with unacceptable vibration and possible damage at certain engine speeds, has been the primary objective of instrument designers working with rapid cyclic variations in crankshaft angular velocity. It has only been in the last few years, with the advent of economical and powerful solid-state electronic circuitry, that it has become practical to consider using these rotational velocity excursions as

[4]Standard Handbook for Mechanical Engineers, pp. 8-100.

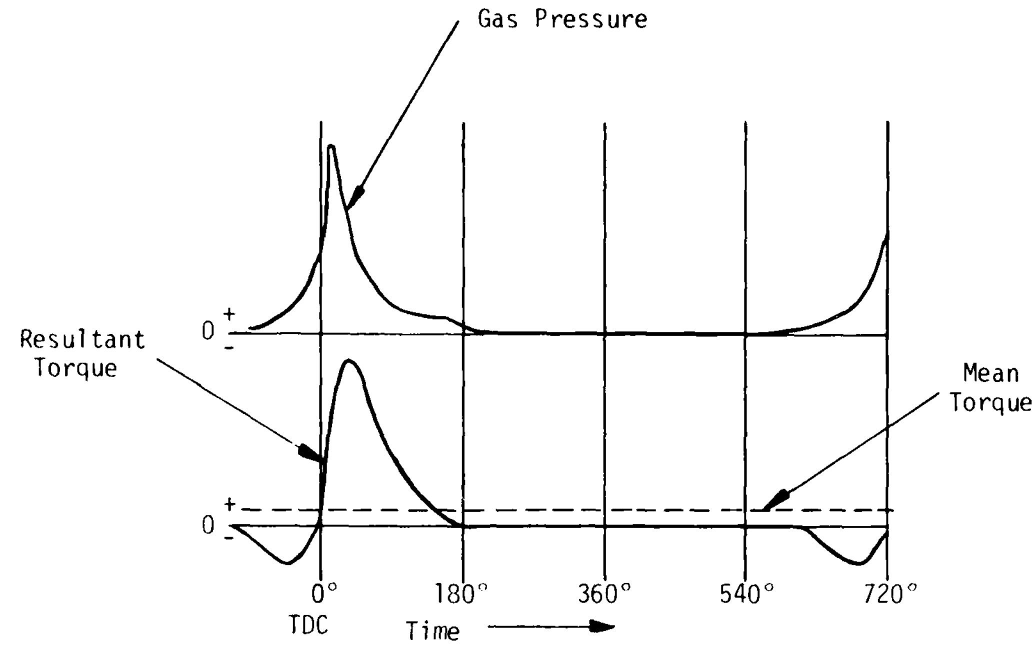

FIGURE 3.1 - TYPICAL CURVE OF GAS PRESSURE VERSUS CRANK ANGLE **AND** RESULTANT CRANKSHAFT TORQUE FOR A FOUR-STROKE CYCLE ENGINE (from Taylor, Reference 3)

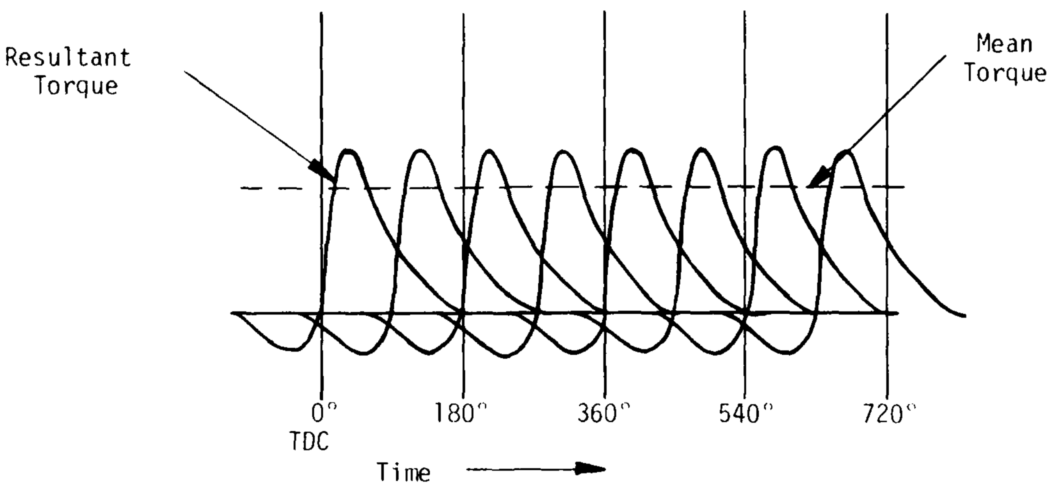

FIGURE 3.2 - CRANKSHAFT TORQUE VERSUS CRANK ANGLE FOR TYPICAL EIGHT-CYLINDER, FOUR-STROKE CYCLE ENGINE

a means to diagnose engine faults. The torsiograph[5] and its many related instruments are satisfactory for measuring the amplitude and frequency of torsional vibrations; but they are not suitable for individual cylinder diagnostic purposes since they cannot provide real-time phase angle information which serves to identify individual cylinders. These units simply allow the engine designer to determine with reasonable accuracy that the crankshaft is not being subjected to forces likely to cause failure.

When using ICAV for diagnostic purposes, the signals resulting from torsional vibrations due to the spring mass constants of the crankshaft system can generally be greatly reduced in magnitude by electrical filtering without reducing the ICAV signal components due to individual cylinder firing events. Power imbalances due to abnormal combustion and certain other engine defects can now be observed as greater or lesser crankshaft accelerations during the portion of rotation which is related to the power stroke of the particular cylinder in question. The highest engine speed that can be satisfactorily accommodated for ICAV diagnosis is dependent upon the spring mass characteristics of the crankshaft assembly in the engine under test since this establishes the lowest torsional resonance frequency of the rotating assembly. This resonance frequency must be appreciably higher than the cylinder firing rate being used for diagnosis. By suitably identifying a cylinder (usually No. 1) in the firing order, it is possible to examine the instantaneous torque contribution and the angular momentum change resulting from the firing of a given cylinder. Because of overlapping torques, engines with many cylinders are more difficult to diagnose by these means since the power impulses are much closer together and there is less tendency for the flywheel to speed up and slow down appreciably in the course of rotation. Bear in mind, however, that engines of <u>many cylinders</u> are precisely the ones in which diagnosis is extremely difficult by <u>any</u> means. It is quite common for a 16- or 20-cylinder engine to suffer a substantial defect in one cylinder and yet display such a small amount of overall power loss that, barring catastrophic failure, the problem goes completely unnoticed in normal day-to-day usage. Instantaneous crankshaft angular velocity presents a means whereby these defects can not only be found, but also attributed to specific cylinders. No alternate, easily implemented means for making this determination has been identified.

3.3 Dynamic Crankcase Pressure (PKD)

Virtually all large engines have some means of measuring the static or average crankcase pressure, which may be either positive or negative depending upon whether an active crankcase scavenging system is used. While this average pressure remains constant, the combustion gas leakage from individual cylinders produces small but definite rapid variations about this average crankcase pressure value. This variation is termed Dynamic Crankcase Pressure, or PKD for short. Engine defects which manifest themselves when

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[5] Bradbury, C. H., Stationary Compression Ignition Engines, E. & F. Spon, Ltd., 1950.

using this diagnostic parameter are related to gas leakage past the piston rings (a small amount of which is normal) or through a hole or crack in a piston. A fast-response, sensitive pressure transducer connected directly to the closed engine crankcase is suitable for PKD measurement. For simplicity's sake, we generally prefer to use a self-generating piezoelectric-type pressure transducer, even though this type of transducer is sensitive to both acoustic noise and mechanical vibration. These "noise" signals are ordinarily of much higher frequency than the crankcase pressure pulsations and may be reduced by filtering. The piezoelectric transducer has the overriding advantage of economy: a cost about five to ten percent of the more complex types and, since it is self-generating, it requires much simpler wiring. This transducer is not satisfactory for making static measurements since it is sensitive to changing pressures only; however, in this case static response is not necessary.

Since the crankcase volume is large in these engines, the magnitude of dynamic pressure variation from a given defect is quite small. In addition, crankcase volume (and therefore pressure) varies slightly during engine rotation (because of the reciprocating motion of the pistons) in a complex way. The strategy we have therefore employed has been to make the transducer and its amplifier very sensitive and then use this excess sensitivity along with filtering flexibility to classify PKD signals for particular engine types. Although the PKD transducer arrangement itself is simpler than the ICAV system, interpretation of the data is often considerably more complex and must be done on an empirical basis for each engine that is to be diagnosed. Just as in the case of ICAV, there is a distinct advantage to presenting and recording these pressure fluctuations real-time and in having a synchronizing (SYNCH) mark that allows us to determine which pressure variations belong to individual cylinders in the firing order.

A further consideration is that, for a particular engine, location of the pressure tap into the crankcase may be a critical factor. It is reasonable to expect that for a given engine type, defects will be more easily seen and more readily diagnosed if the pressure tap is in a propitious location. This location must be determined by trial and error. Similarly, there seems to be no direct analytical way to realize the full potential of this diagnostic technique short of inducing real defects into the engine of interest and also making baseline (no defects) data measurements for comparison.

4. EQUIPMENT DEVELOPMENT

4.1 Instantaneous Crankshaft Angular Velocity (ICAV)

Early in the ICAV test work it became apparent that a bench test rig would be particularly useful in quantifying and verifying the performance of various ICAV detection methods. Figure 4.1 shows several photographs of this test set-up, which indeed proved to be quite useful. The test rig permits known variations in ICAV to be generated over a broad range of operating speeds. Its operation is as follows: A variable-speed electric motor turns the "driving" shaft which carries a 60-tooth gear to generate readout of shaft speed in revolutions per minute (RPM) and a 5.9 kg (13 lb) flywheel to provide large angular inertia and thus assure essentially constant angular velocity of this driving shaft. The driving shaft is connected to a "driven" shaft by means of a Hooke's, or universal, joint. This driven shaft is fitted with a "test" flywheel (with small inertia) made of lightweight foam plastic material. The heavy constant-speed flywheel has a circumference of 30.5cm (12 in), while the lightweight test flywheel is 61cm (24 in) in circumference.

Bench experiments are conducted by using the instrumentation to measure ICAV of the test flywheel as the rotational speed and the angle of the Hooke's joint are varied. The ICAV undergoes a sinusoidal variation twice each rotation, the magnitude of which depends predictably on the angle of "bend" in the Hooke's joint. Ladder tapes of alternate light and dark stripes are installed on the circumference of both flywheels, and these tapes are scanned by an optical pickup sensor. A precision shaft encoder, capable of producing 900 cycles of square wave per revolution, is attached to the driven shaft near the test flywheel. The shaft encoder and the ladder tape/optical scanner systems both operate on the same principle: there is a direct proportionality between the frequency of their electrical outputs and shaft angular velocity. The angle between the driven and the driving shaft (through the Hooke's joint) is calibrated in terms of the so-called K-factor, defined as

$$K = \frac{ICAV_{max} - ICAV_{min}}{ICAV_{average}} ,$$

thus utilizing the mechanical property of the Hooke's joint which specifies that if there is a known angle between the two shafts to which the joint is attached, the motion of the output shaft will vary from the motion of the input shaft in a predictable manner. The angular velocity of the output shaft during each rotation of the input shaft undergoes a variation that can be accurately calculated[6].

As anticipated, initial tests performed with the bench rig verified that the precision optical shaft encoder generates extremely "clean" ICAV

[6]Doty, V., and W. James, Elements of Mechanism, Wiley & Sons, 1954.

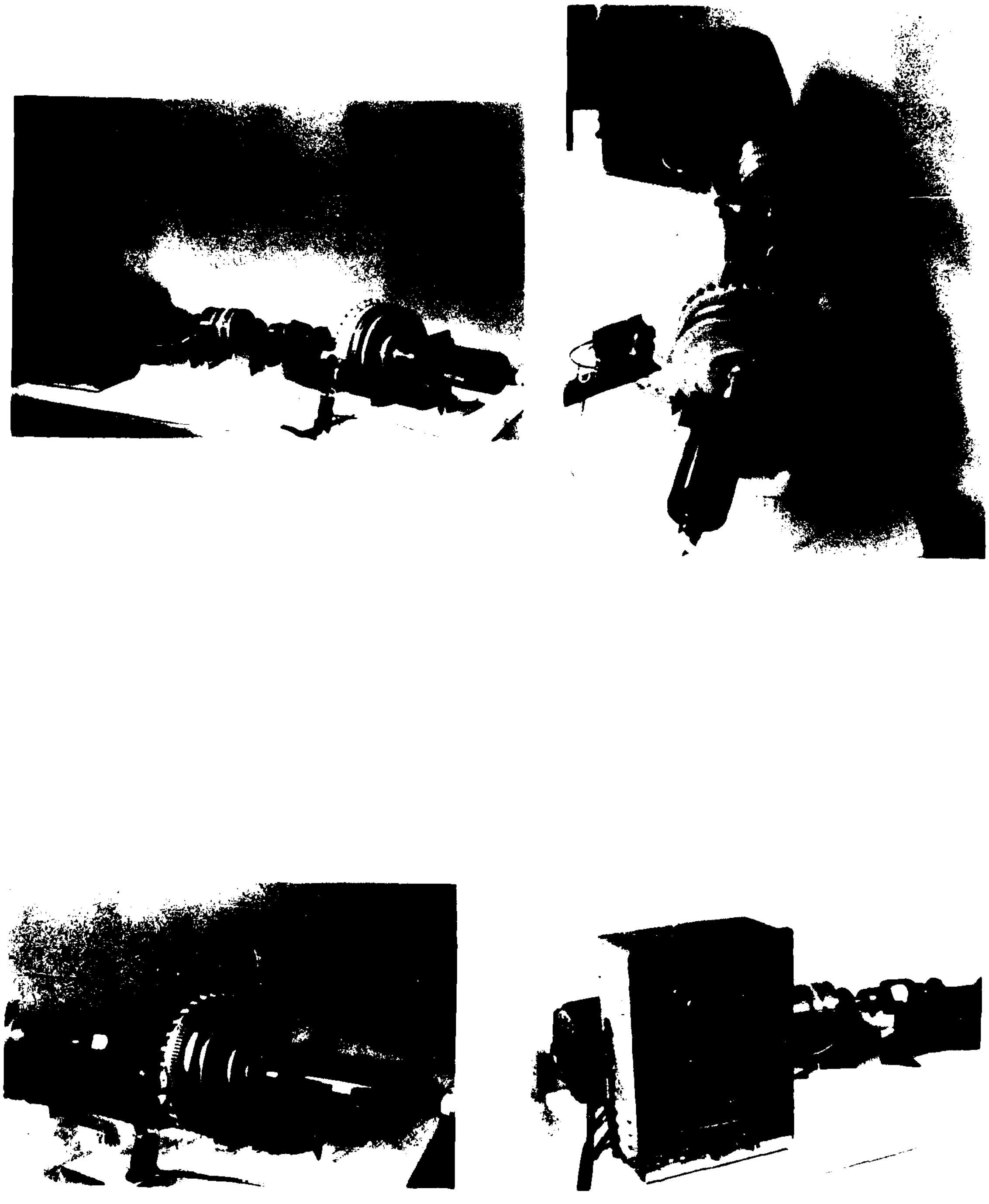


FIGURE 4.1 - VARIOUS VIEWS OF ICAV BENCH TEST RIG

signals. For this reason, the shaft encoder was used as the standard against which other measurement techniques were compared. This device (Model 30G900IDZPA1A, manufactured by Sequential Information Systems, Inc.) is ordinarily used in the direct mode where it produces 900 square wave cycles per revolution. The shaft encoder was used on the Enterprise test engine at SwRI (Section 5.1) during preliminary development work and also on test engines at the ALCO and Fairbanks Morse manufacturing plants (Sections 5.3 and 5.4). All three of these engines were coupled to alternators, and special adapters were fabricated to allow attachment of the shaft encoder to the rear of the alternator shaft. The difficulty (or outright impossibility) of satisfactorily attaching a shaft encoder to actual ship engines in the field necessitated development of a practical alternate angular velocity sensing means, and this situation resulted in development of the optical scanner system using ladder tapes which was alluded to earlier in the description of the bench test rig.

The optical scanner system operates in the following manner. Adhesive-backed tape with alternate light and dark stripes is attached to the rim of the flywheel of the test engine. A small light source in the scanner illuminates a region of the tape (smaller than an individual stripe), and a photo-transistor senses reflected light from the illuminated tape markings as they pass and produces an output signal whose frequency is proportional to angular velocity, just as the shaft encoder does. Thus, output frequency of either system is directly proportional to instantaneous rotational speed. The optical scanner/ladder tape arrangement is equivalent to what is done inside the shaft encoder, but it is not quite as precise due to manufacturing variations in the spacing between and width of the tape marks. Bench tests have established that under average conditions the optical scanner can, with the available ladder tape, resolve K-factors in the range of 0.004 to 0.006. This resolution is two or three times poorer than that obtained with the shaft encoder, but it is considered satisfactory for most diagnostic purposes. More precise ladder tape can be fabricated if the need arises.

Flywheel rotation may also be sensed using the flywheel ring gear teeth and either a magnetic pickup or the optical sensing method described above. In the latter case the optical system illuminates and scans these teeth just as it does the ladder tape marks, and thereby produces a signal which is essentially the same as described previously. As a matter of completeness, ICAV recordings were made using the optical pickup to sense the flywheel teeth on some test engines. However, this work confirmed our suspicion that this is not a particularly satisfactory way to derive ICAV signals since the ring gear provides poor resolution (too few teeth) and, hence, is not precise enough for diagnostic purposes.

A small amount of time and effort was also expended at the bench to verify that ultrasonic doppler is a promising means of obtaining the ICAV signal from a rotating member. With this technique, a beam of ultrasound is directed more or less tangentially toward the edge of the test wheel. The

ultrasonic waves reflected from the wheel edge back to the detector have a doppler frequency shift from their original (transmitted) value because the reflecting surface is moving in relation to the fixed signal source and detector. Since the magnitude of the doppler shift is directly proportional to the instantaneous wheel peripheral speed, it contains the ICAV information of interest. After demonstrating to our satisfaction on the bench rig that it is feasible to use ultrasonic doppler as an ICAV sensor, we halted any further efforts, principally because there is presently no suitable ultrasonic transducer that is commercially available. The bench tests were conducted with a readily available 40 KHz air transducer which, because of band width limitations, will not work at doppler shift frequencies associated with typical flywheel rim speeds. A suitable transducer would have to operate at a frequency greater than 200 KHz, and development of such a unit was beyond the scope of the project. It should be mentioned, however, that this technique holds the promise of being the easiest way of all to obtain ICAV information from an in-service engine. The test operator would simply walk up to the rotating member, point the probe at it tangentially, and obtain the ICAV record.

4.2 Dynamic Crankcase Pressure (PKD)

Figure 4.2 illustrates a simple but quite sensitive piezoelectric pressure transducer fabricated to measure PKD. As can be seen from the sketch, the major components are pipe fittings, the piezoelectric element, and a connector. Total parts cost is less than $10 (in 1979). Its measured sensitivity is about one millivolt peak-to-peak for 2.5cm (one in) of water pressure change. Several of these units have been fabricated and have proven entirely satisfactory. The only difficulties encountered centered around those engines which had very low pressure fluctuations in the crankcase. Therefore, considerably more gain was designed into the signal channels of later test equipment to alleviate this problem.

4.3 TDC Indicator (SYNCH)

A small clamp-on piezoelectric transducer was used to detect the injection event for the No. 1 cylinder in the firing order (see Figure 4.3). During injection, pulsations in the high-pressure injection line produce an electrical output from this transducer which resembles a burst of high-frequency noise and corresponds to the duration of the injection event. Although this particular transducer is sensitive to gross vibration, these unwanted signals have different frequency and amplitude characteristics than those produced by injection. By means of suitable signal processing, the injection event signal was enhanced and used to produce a timing or synchronizing pulse that very nearly coincides with Cylinder No. 1 injection.

4.4 Data Display Methods

Strip chart recordings of ICAV and PKD signals with a trace edge SYNCH mark were obtained by two methods. Initially, a small 50mm (2 in) wide heat-writing galvanometer-type recorder was modified to write fast enough

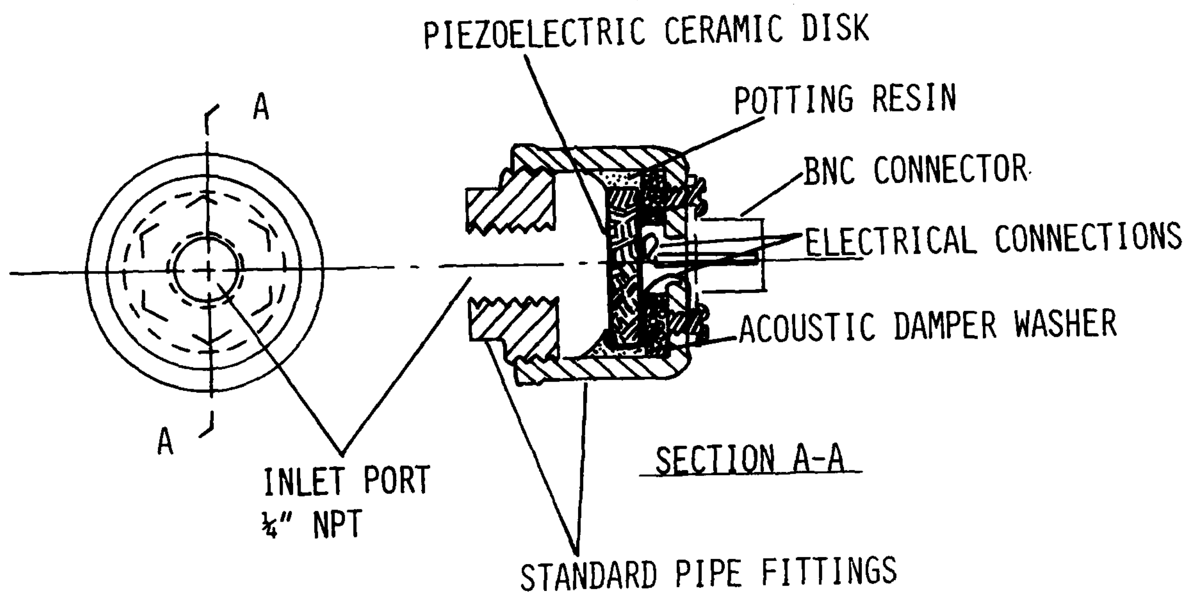


FIGURE 4.2 - PIEZOELECTRIC TRANSDUCER FOR MEASUREMENT OF DYNAMIC CRANKCASE PRESSURE

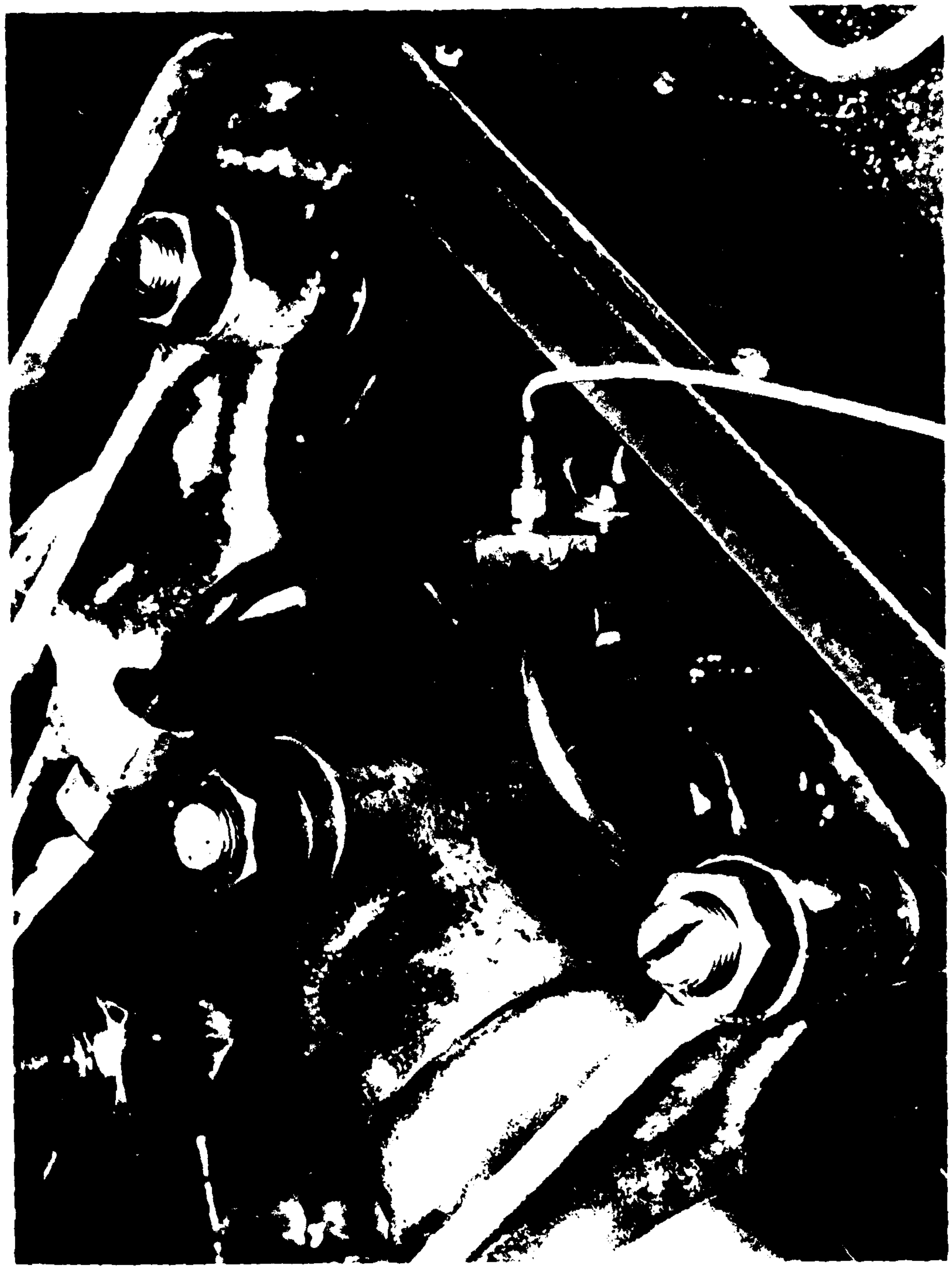


FIGURE 4.3 - TDC INDICATOR TRANSDUCER INSTALLED ON NO. 1 CYLINDER INJECTION LINE

for direct real-time chart recording. The data shown in later sections (5.1 and 5.2) were obtained this way. This method was at best marginally satisfactory since we often needed to analyze ICAV harmonic components with frequencies at or beyond the response frequency of the galvanometer. For subsequent tests, data were recorded on magnetic tapes at 38 cm/sec (15 in/sec) and then played back onto the strip chart recorder at 2.4 cm/sec (15/16 in/sec). This 16:1 speed reduction lowered signal frequencies by the same ratio and therefore allowed a conventional strip chart recorder to accurately reproduce the waveforms. This process resulted in much better hard-copy records and appeared to be the only practical method for use in any field-worthy prototype diagnostic system that might be developed.

In all cases, signals were monitored on a conventional oscilloscope during the various test series.

4.5 Prototype Diagnostic Hardware

4.5.1 Diagnostic System Mk I

Figure 4.4 is a block diagram of this ICAV detector, which was used during ICAV tests with the bench rig, the Enterprise engine at SwRI, and the DURABLE's ALCO engine. The complete schematic diagram of the Mk I system is contained in Appendix A for reference purposes. The detector was designed to operate in two test modes, as described in the following paragraphs.

Consider the first operating mode (solid lines) in which the optical sensing head "reads" a ladder tape that is illuminated by a suitable light source. Passage of the light and dark stripes is sensed by a photo-transistor (type MRD300) whose output feeds into a 100X (one hundred times) amplifier, then to a zero crossing detector whose square wave output goes to a phase detector which is part of a phase locked loop (PLL) system. The output of the phase detector is an electrical (error) signal whose amplitude is proportional to the phase difference between the ladder-tape derived input signal and the voltage controlled oscillator (VCO) output. After suitable filtering, this error signal is in turn used to control the frequency of the VCO, thereby closing the control loop. The VCO is then forced to exactly track the ladder tape signal, and the error voltage that forces the VCO to follow the frequency excursions of the input signal (around some average value) is the ICAV signal.

We are employing here a simple and very sensitive method of frequency modulation (FM) detection, and the integrated circuits (IC) employed are of the same type found in current FM receivers. Note that the PLL detection system described above produces an output signal only when crankshaft angular velocity (and, therefore, the tape scanner output frequency) varies about its constant speed value at a rate which produces electrical signals that can pass through the PLL feedback circuit filter. Since this filter is of low pass configuration, the PLL will track (and produce a signal output for) low rate (frequency) ICAV, but not for higher frequency noise components which are of no interest. The VCO and zero crossing detector outputs are fed into a separate circuit designed to give

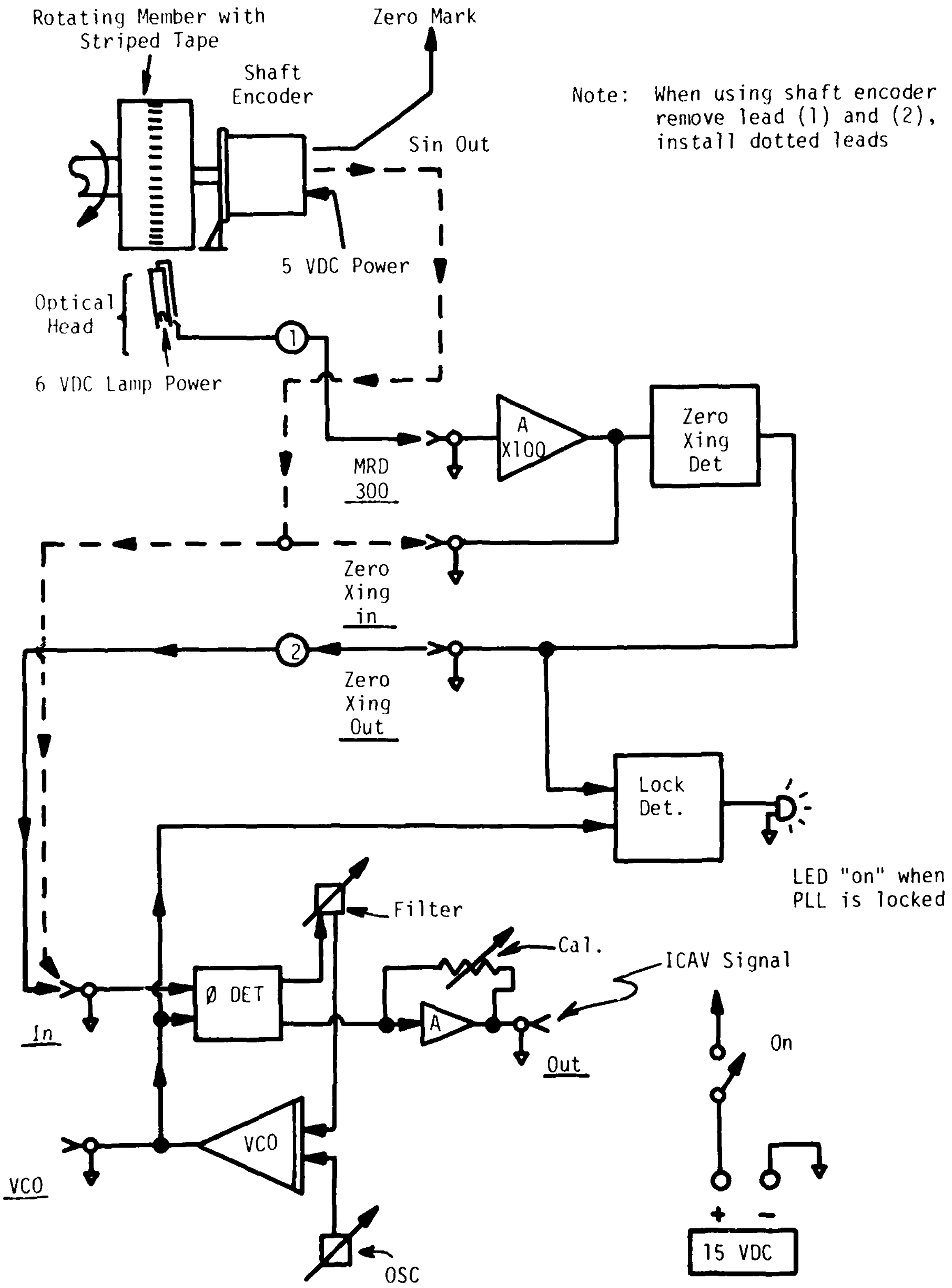


FIGURE 4.4 - DETECTOR BLOCK DIAGRAM OF MARK I ICAV

indication (lighted LED lamp) of when the PLL is locked onto the ladder tape input signal.

The second operating mode of the Mk I detector is shown with dotted lines on Figure 4.4. Leads marked 1 and 2 in the figure are removed when it is desired that the unit function with the output from the shaft encoder instead of that from the optical pickup and ladder tape. The sine wave output of the shaft encoder is fed to the zero crossing detector and the PLL directly; otherwise, the system functions as already described.

4.5.2 Diagnostic System Mk II

Tests conducted on board the DURABLE disclosed the need for more flexibility in the field test equipment and, in response to this need, a redesign of the electronic circuitry was undertaken. A schematic of the Mk II is in Appendix B. This unit has been found to be entirely satisfactory, and we believe the circuit techniques embodied in this design are generally suitable for use in later generations of diagnostic equipment.

As a first step, several new PLL circuits were evaluated, and it was decided to switch to RCA type CD 4046. This PLL IC is unusual in that it has two built-in phase detectors; one is a special type employing edge-triggered logic which provides an extremely wide locking range; the other is a more conventional low-noise type. The Mk II test unit can thus provide two varieties of PLL ICAV detection and, in addition, is capable of ICAV detection by means of direct time integration of the pulses out of either the shaft encoder or the optical scanner. Time integration detection is the method most frequently employed in the past, both in our ICAV work and in commercial torsional analysis equipment. It is simple and direct, but rather insensitive, and it suffers from a much poorer single-to-noise ratio (S/N) than the PLL scheme. The Mk II also incorporates signal conditioning circuitry for deriving the SYNCH signal from the transducer attached to a selected injection line. In addition, more flexibility was built into the Mk II regarding available amplifier gain and its control.

Figure 4.5 shows in block diagram form the general functions and switching provisions of Mk II. Referring to the figure, it can be seen that ICAV may be sensed using ladder tape or gear teeth with the optical scanner, or it can use the shaft encoder. The same amplifier which is used with these sensors may also be used as a preamplifier for the PKD transducer. This amplifier output can be switched through an adjustable filter and then back through the variable-gain signal amplifier for PKD presentation, or it can be fed into a zero crossing detector to produce a signal suitable for ICAV detection. The zero crossing detector output may be switched to the PLL circuit or to the time integrator ($T\Sigma$) as desired. In the PLL mode, either of the two phase detection methods may be switched in for comparison. An indicator lamp shows when the circuit is locked to the input signal. An input switch for the adjustable filter circuit allows selection of PKD (as mentioned above), PLL output, or the output of the time integrator circuit for ICAV presentation. After filtering, the signal goes to a variable-gain signal amplifier before appearing at the output connector. Signal conditioning for the data synchronization (SYNCH) signal incorporated into Mk II is as shown in the block diagram.

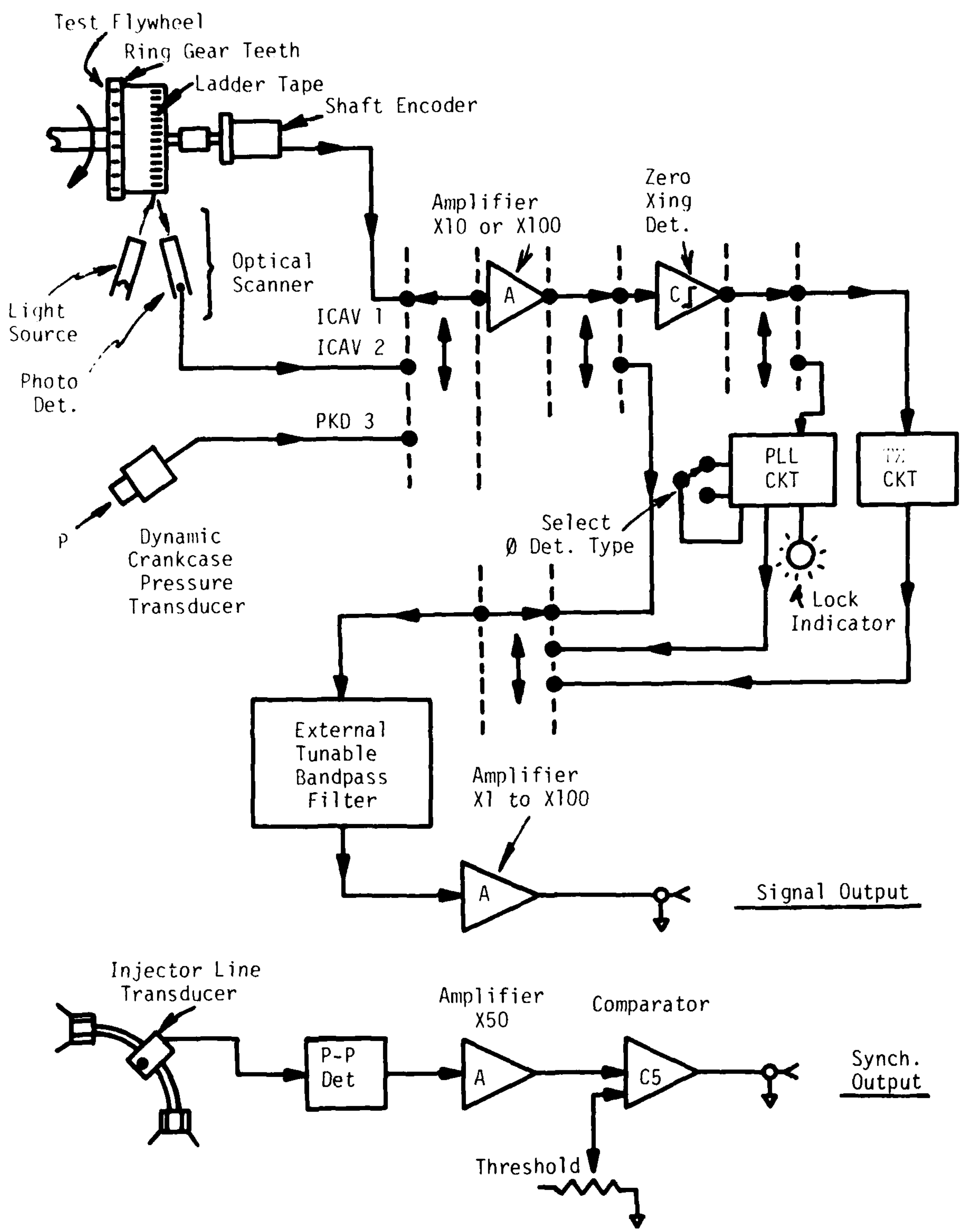


FIGURE 4.5 - DETECTOR BLOCK DIAGRAM OF MARK II ICAV

5. ENGINE DIAGNOSTICS TEST PROGRAM

5.1 Enterprise Engine at SwRI

5.1.1 Test Procedures

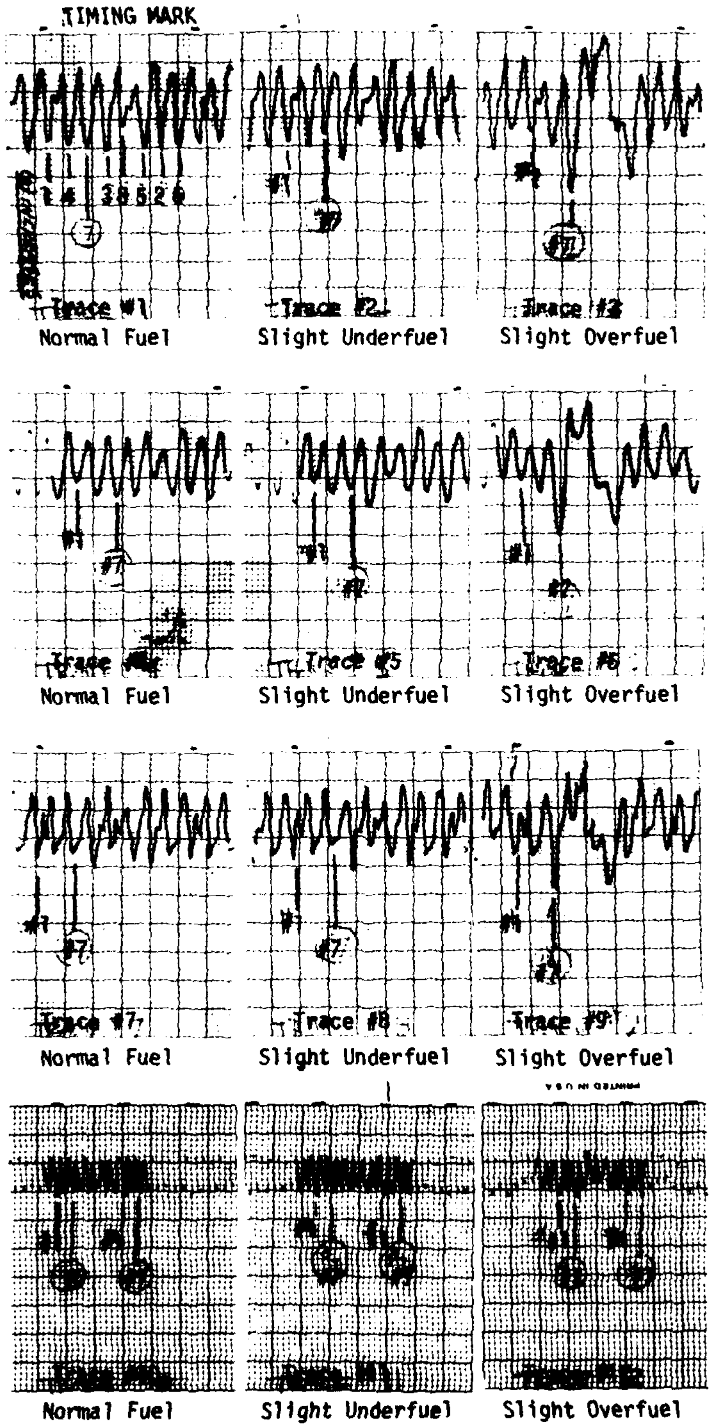
This engine is an eight-cylinder, four-stroke cycle, in-line unit with firing order 1-4-7-3-8-5-2-6. The third cylinder in the order (No. 7) was modified so that the injector pump fuel rack could be controlled independently of the engine governor setting. In the discussion of test data for this engine, as well as all others, "normal fuel" indicates the normal injector rack position for a particular engine speed, "low fuel" (or "underfuel") indicates a reduced rack setting, and "excess fuel" (or "overfuel") means that the controlled cylinder rack setting was increased until a slight engine knock was heard. No attempt was made to determine exactly what underfuel and overfuel meant in terms of percentage cylinder power imbalance since there was no provision for loading this engine. Under no-load conditions, ICAV variations induced by fuel changes in one cylinder are very small; hence, the Enterprise was considered to be a "worst case" engine. Therefore, it was thought that instrumentation capable of resolving ICAV waveform differences in this situation should be sensitive enough to work satisfactorily with almost any other large engine.

Piezoelectric pressure transducers were installed to obtain . baseline (normal) PKD data and also No. 1 cylinder firing pressure for use as a mark for data synchronization. As described elsewhere, this synchronization was obtained more easily in later tests by sensing the injection event directly off the high-pressure injection line of the selected cylinder.

5.1.2 Data Analysis

Tests conducted with this engine produced chart recordings of ICAV data under both normal and abnormal fueling conditions as shown in Figure 5.1. The quality of the original chart recordings is rather poor. In order to make the traces more legible for reproduction, portions of them were carefully traced over to clarify the features being described. However, the data shown are faithful, hard-copy representations of real-time signals observed during the tests.

The traces shown in Figure 5.1 illustrate the effect on ICAV of cylinder power imbalance caused by fueling variations. Different degrees of electrical filtering were used as noted to show that effect on the observed ICAV frequency spectrum. At an engine speed of 240 RPM (Traces 1 to 9, inclusive), it is easily seen that the ICAV signal is optimized when the filter bandpass is set to the 5 Hz to 40 Hz range (Traces 4 to 6). The signal obtained with a filter bandpass of 5 Hz to 65 Hz (Traces 1 to 3) is slightly degraded by the higher-frequency components that are passed by the filter. This degradation is even more evident in Traces 7 to 9, where the



Engine Speed: 240 RPM

Filter Bandpass: 5 Hz to 65 Hz

Engine Speed: 240 RPM

Filter Bandpass: 5 Hz to 40 Hz

Engine Speed: 240 RPM

Filter Bandpass: 5 Hz to 350 Hz

Engine Speed: 900 RPM

Filter Bandpass: 5 Hz to 350 Hz

FIGURE 5.1 - ENTERPRISE ENGINE ICAV RECORDED WAVEFORMS

upper bandpass limit was increased to 350 Hz. These examples illustrate the importance of optimum ICAV signal filtering. At an engine speed of 900 RPM (Traces 10 to 12), the higher-frequency ICAV signal does not lend itself to ready interpretation due both to the limited frequency response of the direct-writing chart recorder and to the fact that only very small variations in ICAV are present at the higher engine speed. Chart recorder presentation can be upgraded, but it is our opinion that high-(engine) speed ICAV is, for several reasons, inherently less reliable for diagnostic purposes than that obtained at lower speeds. These points are discussed in somewhat greater detail in later sections of this report.

Figure 5.2 illustrates real-time dynamic crankcase pressure (PKD) recorded directly from the piezoelectric pressure transducer connected to the engine crankcase. No known engine defects were present when this signal was recorded. It can be seen that the dynamic pressure variation is small, regular, and has the form of two pressure pulses per cylinder firing event. These pressure variations are the result of changing crankcase volume which accompanies normal piston motion during crankshaft rotation. It appears that use of this waveform would be limited to detecting only gross changes in PKD.

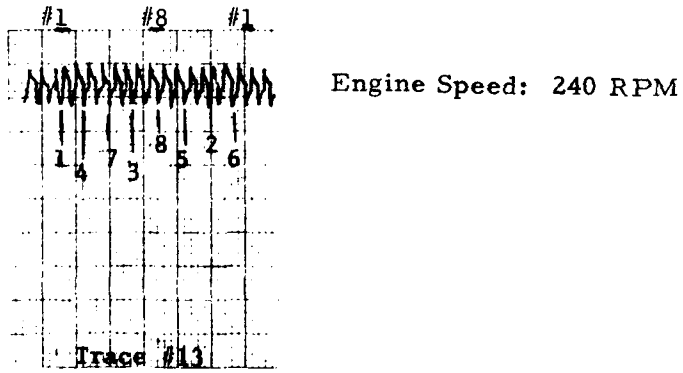
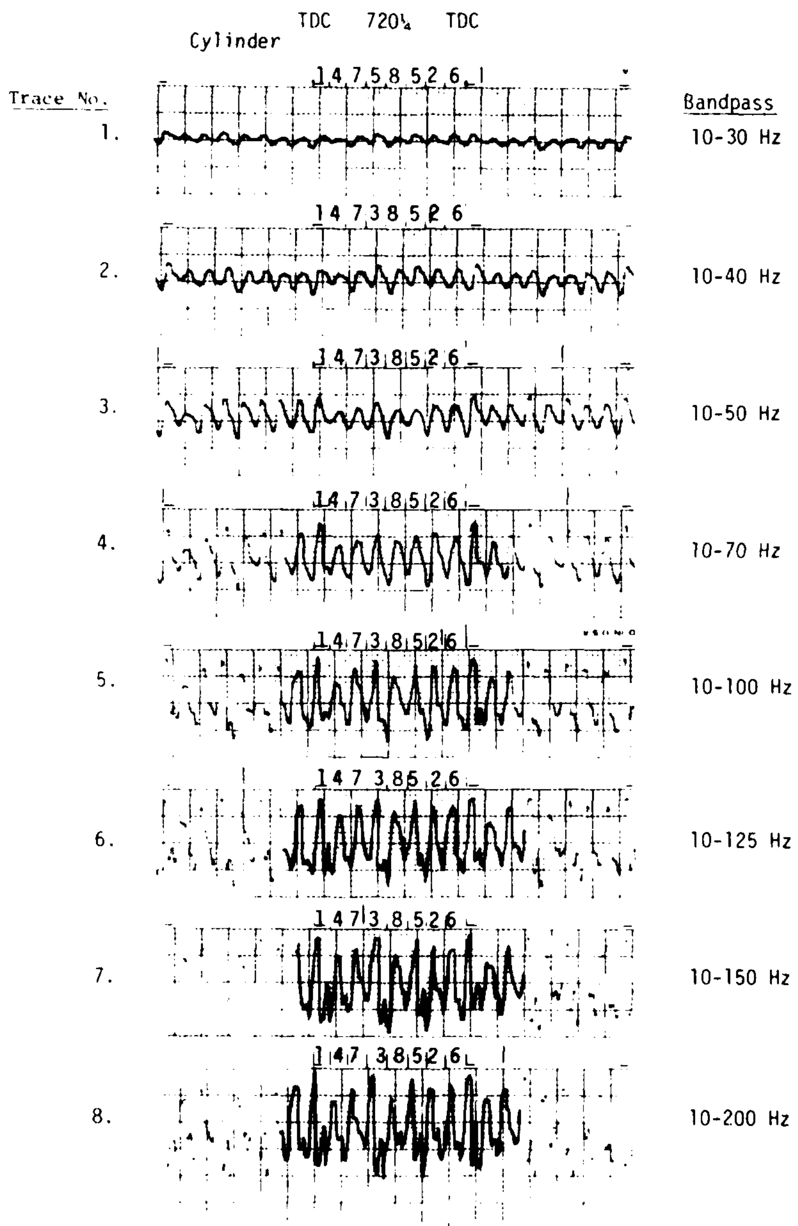


FIGURE 5.2 - ENTERPRISE ENGINE DYNAMIC CRANKCASE PRESSURE RECORDED WAVEFORM

The preceding ICAV data were obtained using the optical shaft encoder and the Mk I detector. Later, after satisfactory development of the simplified ladder tape sensing technique and construction of the Mk II detector, baseline ICAV data were once again obtained from the Enterprise engine under normal operating conditions. Figure 5.3 contains these data, which illustrate once again the pronounced effect filtering has on ICAV signals. The ICAV signal fundamental was at 30 Hz (450 RPM/60 x 4 cylinders firing each revolution). The upper filter rolloff frequency was increased in steps with engine speed held constant, and a trace was recorded at each



(1) ICAV Fundamental Freq. 30 Hz
(2) 450 RPM, Normal Engine
(3) ICAV Increases Upward on Traces

FIGURE 5.3. - BASELINE ICAV TRACES FROM ENTERPRISE ENGINE UNDER NO-LOAD CONDITIONS, SHOWING THE EFFECTS OF VARIOUS DEGREES OF SIGNAL FILTERING ON THE ICAV SIGNAL

setting of the filter bandpass. Immediately after Traces 5, 7, and 8 were made, a photograph of the monitor oscilloscope trace was taken for comparison purposes (Figure 5.4). The two sets of traces generally contain the same information, but the oscilloscope shows greater detail in the form of high frequency components. The chart recorder frequency response begins to fall off rapidly at about 100 Hz, and this effect can be seen by comparing the photographs with the chart traces when the filter bandpass is widened. It was beyond the scope of this work to attempt to determine the diagnostic significance (if any) of these higher frequency components.

5.1.3 Conclusions

We conclude from these tests that:

- ICAV can provide diagnostic information related to cylinder power imbalance when applied to engines of the same type as the Enterprise test engine.

- The ladder tape/optical sensor offers a practical means of deriving ICAV signals from large diesel engines which cannot accommodate a shaft encoder.

- PKD was not pursued past baseline data since defects could not be induced in the Enterprise engine that would influence PKD; however, we may conclude that its PKD waveform was of the type expected.

5.2 ALCO 16V 251B Engine Onboard USCGC DURABLE (WMEC 628)

5.2.1 Test Procedures

This series of tests of the ICAV and PKD prototype instrumentation was conducted on-board the medium-endurance cutter (MEC) DURABLE in Brownsville, Texas. This vessel is powered by two 16-cylinder ALCO 251B diesel engines, each rated 2500 Hp at 1200 RPM. The engines rotate in opposite directions and have different firing orders (Appendix C). The purpose of these tests was to (1) gain experience in use of the diagnostic techniques with an in-service Coast Guard engine, (2) obtain ICAV data from an engine that could be operated under at least a slight load.

The tests were conducted during a two and one-half day period. First, an SwRI technician set up the prototype instrumentation and readout devices (strip chart recorder and oscilloscope), laid a piece of dual-track ladder tape around the perimeter of the port engine flywheel, installed the PKD pressure transducer in the oil dipstick tube, and installed a clamp-on type pressure transducer on the No. 1 cylinder injection line for SYNCH. The engine was then operated briefly to determine that all instrumentation components were functioning properly.

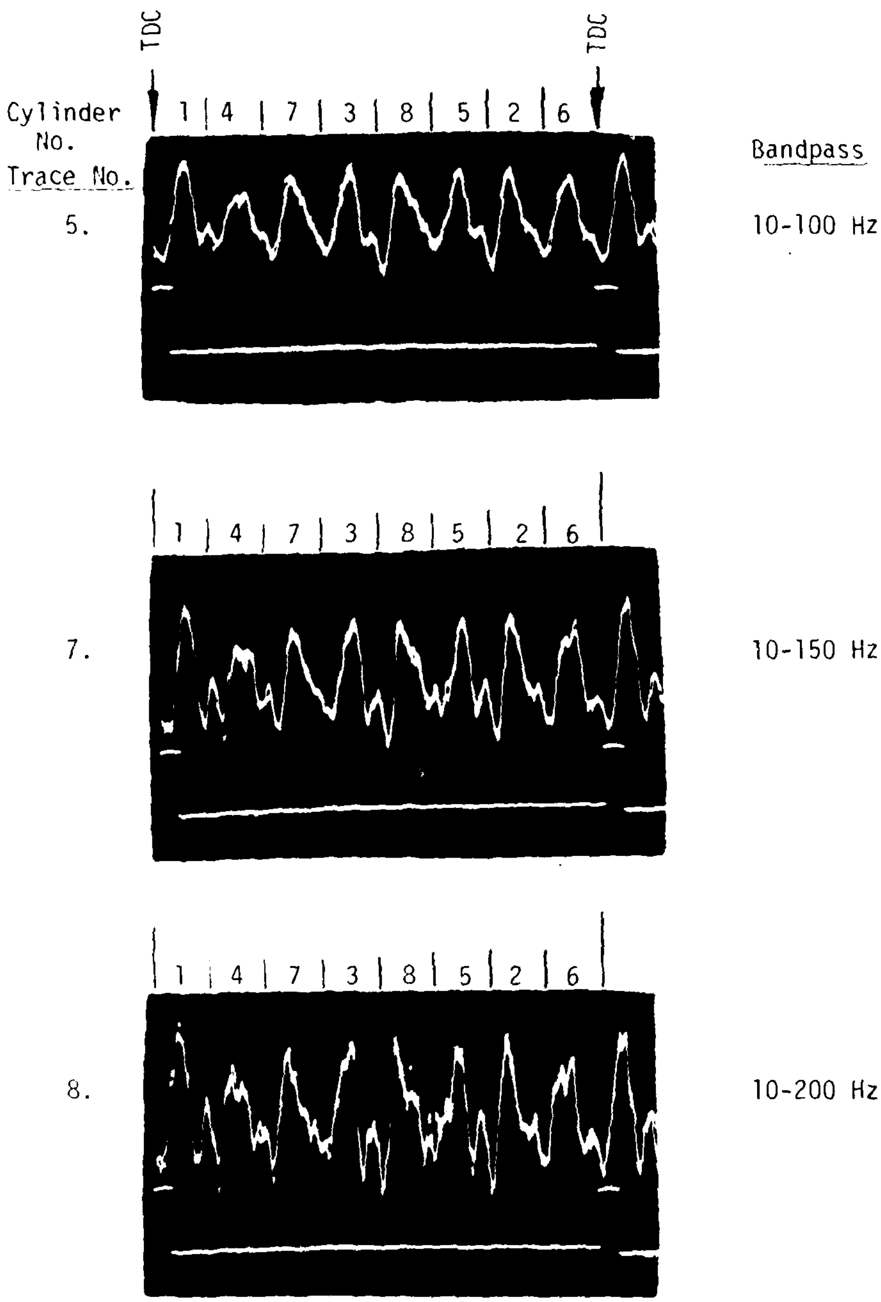


FIGURE 5.4 - OSCILLOSCOPE PHOTOGRAPHS TAKEN IMMEDIATELY AFTER CHART TRACES RECORDED

5.2.2 Data Analysis

This on-board demonstration presented several potential problems that were detailed in a letter to the Technical Contract Monitor at TSC. Briefly, the points of concern involved the short time available to optimize the instrumentation for use on the ALCO engine (at that time an unknown entity), the fact that there would be limited means available to induce or simulate engine malfunctions and, finally, lack of knowledge about the mechanical condition of the engine.

In retrospect, it can be said that only the latter point had a significant bearing on the results of these tests. The instrumentation was readily adapted to the engine, and signal response was judged to be adequate for evaluation. We were able to induce an underfuel or overfuel condition in individual cylinders by means of a simple manipulation of the appropriate injector racks, and this technique was helpful in evaluating the ICAV measurement. However, no means was available to induce crankcase blowby conditions required for a true test of the PKD measurement. The third problem mentioned above--namely, the lack of knowledge concerning the baseline engine condition--was the most serious obstacle. This statement will be borne out in the data analysis that follows, where difficulties were encountered in trying to decide whether an observed signal artifact represented an engine malfunction (already present) or an anomaly in the signal produced by the instrumentation itself.

In any case, the various tests for record were accomplished. The keys to the test conditions are given in Table 5.1 and are explained as follows. Twenty-four runs were conducted. Engine speed for most of these tests was 435 RPM; three tests were conducted at 700 RPM. The engine was operated at both speeds with the clutch disengaged (an essentially unloaded operating condition) and at the lower speed with the clutch engaged and approximately two feet of propeller pitch applied (slight load). Higher engine loads at 435 RPM, and operation under any load at 700 RPM, were precluded by the fact that the cutter was tied up at the dock, and such operation under these static conditions was deemed inadvisable by ship's engineering staff.

Initial tests were performed with the ICAV optical scanner using each of the two ladder tape tracks and also the ring gear teeth on the flywheel. One tape track had alternating dark and light bands, each 1.27mm (0.05 in) wide. The space between leading edges of adjacent dark bands was therefore 2.5mm (0.1 in), and this tape is referred to as the narrow track. The second tape also had dark bands of 1.27mm (0.05 in) width, but they were separated by 3.8mm (0.15 in); the distance between leading edges of consecutive dark bands was therefore 5.1mm (0.2 in), and this tape is referred to as the wide track. The narrow band track thus has 394 dark stripes per meter (10 per in), while the wide band track has one-half as many.

TABLE 5.1 - KEYS TO CONDITIONS FOR ENGINE DIAGNOSTIC TESTS--USCG CUTTER DURABLE

Run No.	Engine RPM	Clutch Status	Light Beam Reflector (ICAV)	Filter Band-pass, Hz	Inj. Rack Adjustment	Affected Cylinder
1	435	In*	Narrow Track	16-85	Normal	None
2	435	In*	Wide Track	16-85	Normal	None
3	435	In*	Ring Gear	16-85	Normal	None
4	435	Out	Narrow Track	16-85	Normal	None
5	435	Out	Wide Track	16-85	Normal	None
6	435	Out	Ring Gear	16-85	Normal	None
7	435	In*	Narrow Track	16-85	Normal	None
8	435	In*	Narrow Track	16-85	Overfuel	5L
9	435	In*	Narrow Track	16-85	Underfuel	5L
10	435	Out	Narrow Track	16-85	Normal	None
11	435	Out	Narrow Track	16-85	Overfuel	5L
12	435	Out	Narrow Track	16-85	Underfuel	5L
13	435	In*	Narrow Track	16-85	Normal	None
14	435	In*	Narrow Track	16-85	Overfuel	8L
15	435	In*	Narrow Track	16-85	Underfuel	8L
16	435	Out	Narrow Track	16-85	Normal	None
17	435	Out	Narrow Track	16-85	Overfuel	8L
18	435	Out	Narrow Track	16-85	Underfuel	8L
19	700	Out	Narrow Track	75-110	Normal	None
20	700	Out	Narrow Track	75-110	Overfuel	5L
21	700	Out	Narrow Track	75-110	Underfuel	5L
22	435	Out	Narrow Track	10-50	"Normal"}	None
23	435	Out	Narrow Track	10-50	"Overfuel"}	8L
24	435	Out	None--PKD	N.A.	Normal	None

*Approximately 2 ft. of propeller pitch applied.
}Run during initial equipment check-out. Injector in Cylinder 8L later found to have loose rack, resulting in unknown abnormal fueling for that cylinder.

NOTE: Engine rotates in counterclockwise direction with firing order 1R, 1L, 4L, 4R, 7R, 7L, 6R, 6L, 8R, 8L, 5R, 5L, 2R, 2L, 3R, 3L. (See Appendix C)

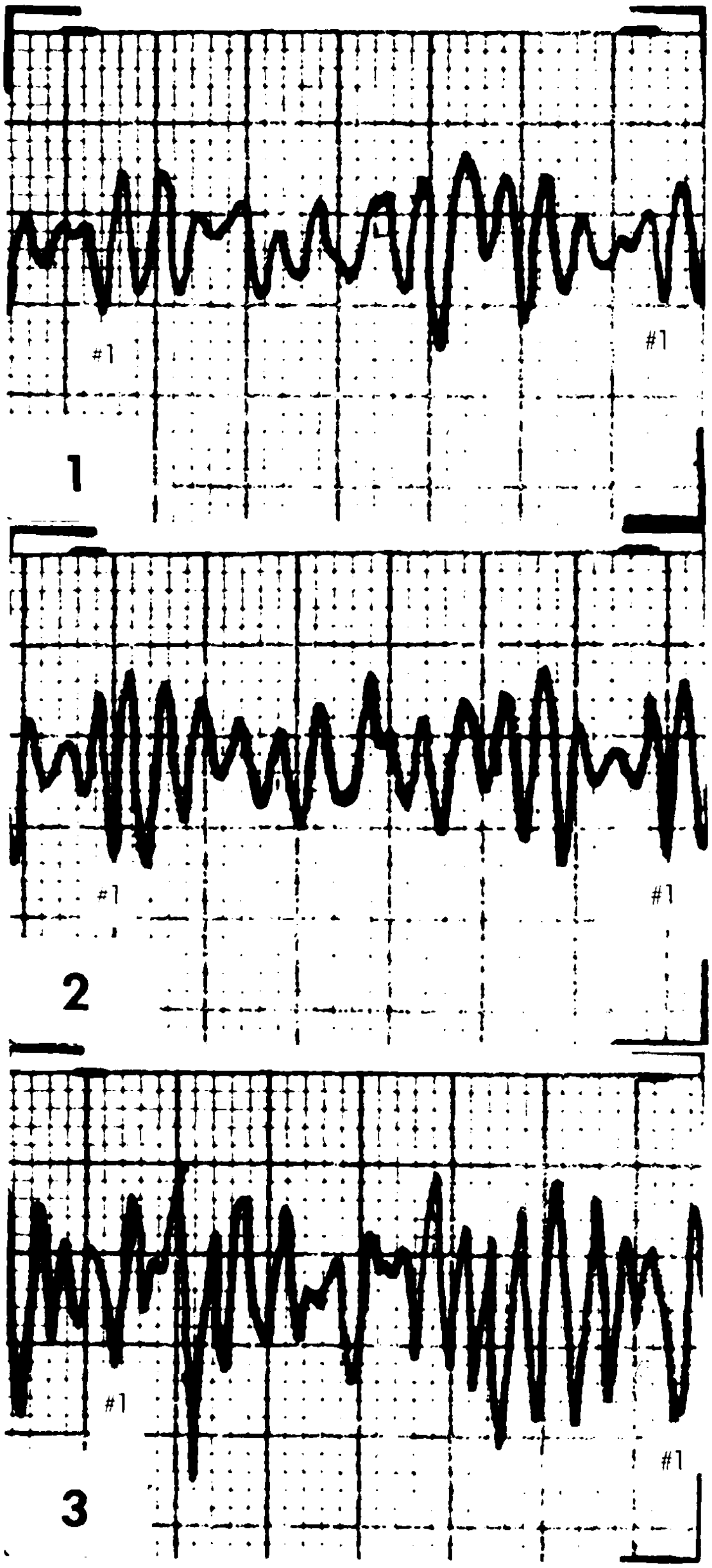
The ALCO 251 flywheel circumference is approximately 4.1 meters (13.5 ft), so the total number of dark stripes around the flywheel perimeter was 1620 and 810, respectively, for the two tape tracks. By way of comparison, there were approximately 300 ring gear teeth on the flywheel, and the optical shaft encoder used in tests at SwRI produced 900 pulses per revolution. Therefore, each of the tape tracks in principle has a potential resolution equal to or greater than that of the shaft encoder, all other factors being equal. These comments also apply to ALCO and Fairbanks Morse engines used in later tests except that some did not have ring gear teeth on their flywheels.

Filter bandpass width for the ICAV signal was optimized for each test condition and, as it turned out, the only major change in the bandpass was necessitated by the high speed (700 RPM) tests. Tests were conducted at baseline (normal) conditions and with overfuel and underfuel conditions in two cylinders (though not at the same time). These two cylinders were Nos. 5 and 8 on the left (L) engine bank, and they occur as Nos. 12 and 10 in the firing order, respectively.

The strip chart traces recorded real-time were somewhat faint, with individual peaks close together due to the relatively slow chart speed available (about 10 cm per second). In order to facilitate interpretation of these traces, a single firing order cycle (obtained over two engine revolutions) of the waveform was selected for enhancement and enlargement. The enhancement again consisted of carefully tracing over the waveform with a fine-point pencil, and then these enhanced traces were enlarged photographically. The traces were not substantially altered by this process. Two further aids to interpretation were added to these reproductions. First, the pressure impulse from the No. 1 cylinder injection event was recorded as a horizontal dash at the top of each chart. This SYNCH mark was used to locate the ICAV peak for the No. 1 cylinder, and this peak has been so labeled at the beginning and end of each cycle on the traces. Second, for those tests where an abnormal fueling condition was induced, the cylinder so affected has been indicated.

Figures 5.5 and 5.6 (Traces 1 to 6) compare baseline ICAV signals from the two tape tracks and the ring gear teeth with the engine in loaded and unloaded operating modes, respectively, at 435 RPM. As expected, the signal produced by the two reflecting tapes is superior to that obtained by reflecting the light beam off the ring gear teeth. Upon examination it appears that, for reasons unknown, the waveform obtained by use of the wide tape track offers slightly more detail than does that from the narrow track. However, it was decided at the time that the narrow track should be used for all subsequent tests since it produced the greatest number of reflections per revolution and should (theoretically) give superior resolution to the waveform.

Comparing individual cylinder impulses (flywheel acceleration is toward the bottom of the chart) in these traces, it can be seen that those made with the engine under load are more regular and of slightly greater

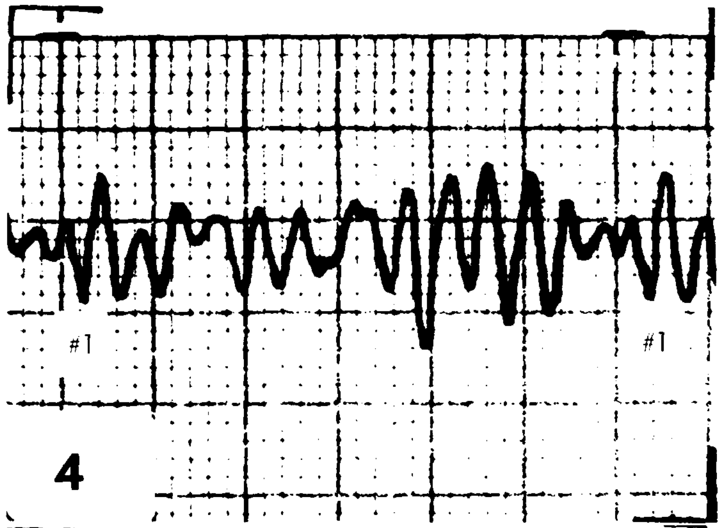


Narrow Optical Track Tape,
16-85 Hz Bandpass

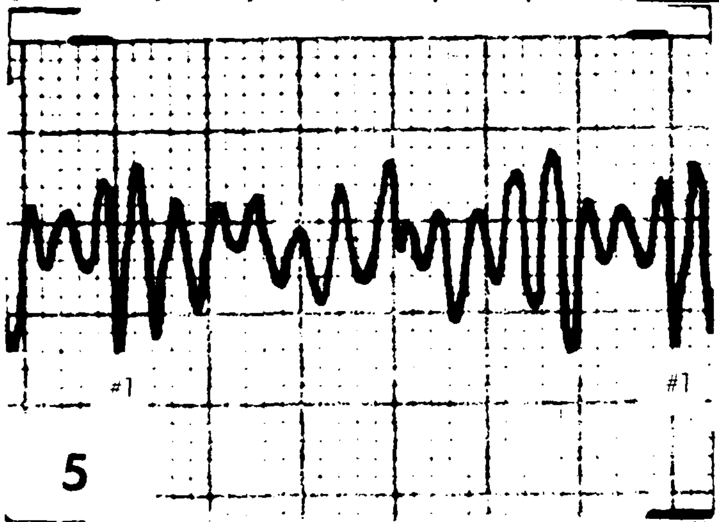
Wide Optical Track Tape,
16-85 Hz Bandpass

Ring Gear Teeth,
16-85 Hz Bandpass

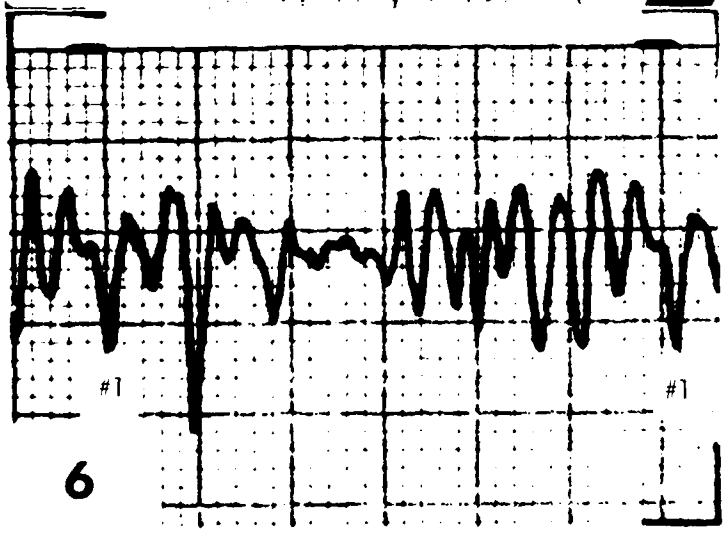
FIGURE 5.5 - ICAV FOR ALCO ENGINE IN MEC DURABLE,
UNDER LOAD AT 435 RPM, NO KNOWN ENGINE DEFECTS PRESENT



Narrow Optical Track Tape,
16-85 Hz Bandpass



Wide Optical Track Tape,
16-85 Hz Bandpass



Ring Gear Teeth,
16-85 Hz Bandpass

FIGURE 5.6 - ICAV FOR ALCO ENGINE IN MEC DURABLE,
NO-LOAD OPERATION AT 435 RPM, NO KNOWN ENGINE DEFECTS PRESENT

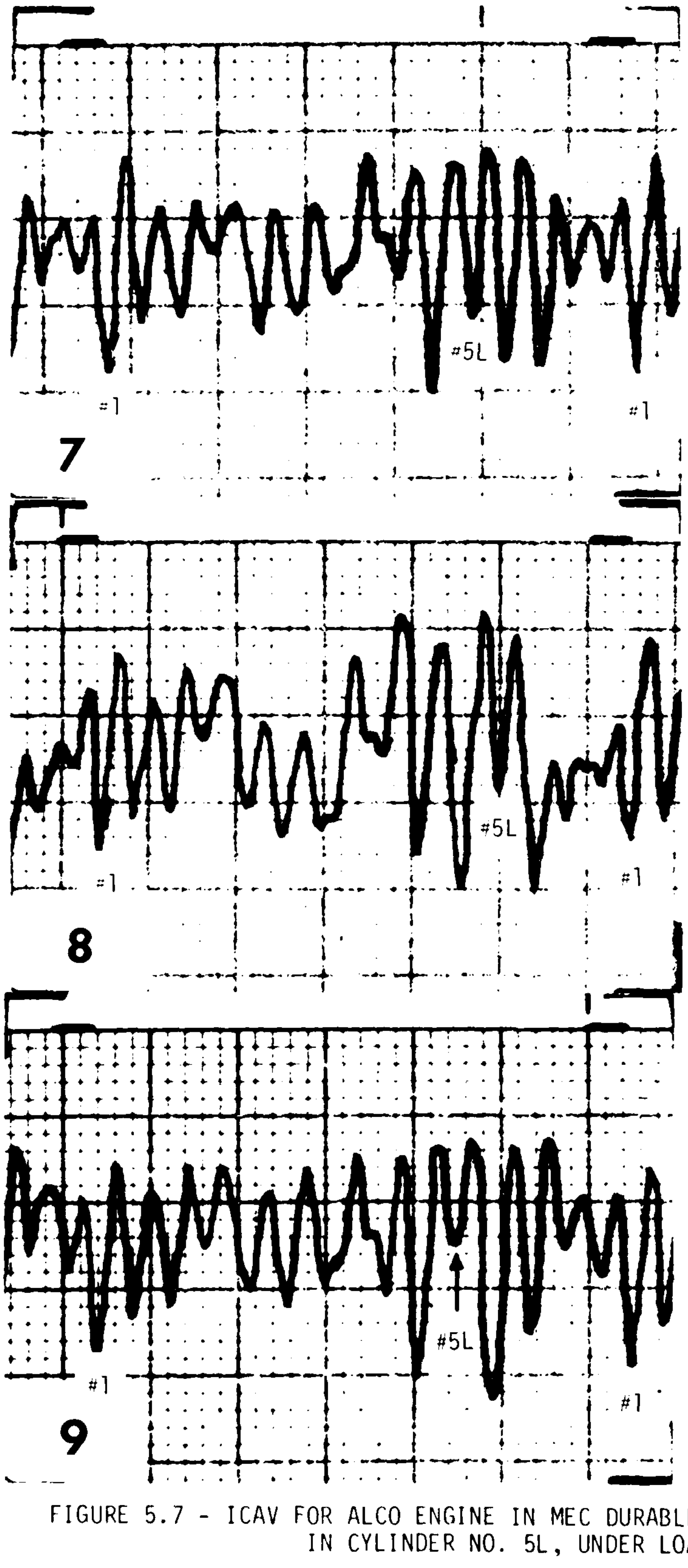
amplitude than those made in the unloaded condition, even though the load we were able to apply at dockside was rather small. Again, this result was expected; however, the traces obtained without load are not markedly inferior. The next thing to note is that several of the impulse waveforms, regardless of the signal source, are irregular in shape. If one counts the number of impulses per cycle in these traces, it is found that one or two impulses are either missing or are extremely small in amplitude and hard to discern. These impulses lie in the middle of the cycle (firing order) in an area that is generally characterized by "soft" (i.e., low amplitude) peaks. These data led us to suspect that several injectors might not be functioning properly in the test engine; however, lack of knowledge concerning the mechanical condition of the engine precluded any definite conclusion along these lines.

The signals from the ring gear teeth actually have one extra impulse per cycle. This condition is probably the result of stray light reflections from the machined surface of the teeth, and is of little concern since no plans currently exist to use the teeth as a signal source. These traces were taken only for comparison purposes.

Figures 5.7 through 5.10 display ICAV with a fuel defect in two different cylinders (though not simultaneously), with engine load as noted. Each group of three traces follows the same sequence: normal fuel, overfuel, and underfuel. All data were taken from the narrow tape track. In each case, the amplitude of the impulse for the cylinder with the fueling anomaly displays a change (increase or decrease) which is consistent with the overfuel or underfuel condition. The change is slightly more evident for Cylinder 5L than it is for Cylinder 8L. The apparent reason for this is that 8L is in a portion of the firing order which is characterized by the low amplitude signals mentioned previously. As expected, the effects of the fueling anomalies were enhanced by operating the engine under a slight load.

After studying the results obtained under baseline and abnormal fueling conditions, we speculated that the test engine probably had some fueling imbalance in portions of the firing order, particularly Nos. 4, 8, 9 and, perhaps, 15 and 16 (Cylinders 4R, 6L, 8R, 3R and 3L). In an effort to make this more than just speculation, we contacted the Engineering Officer of the DURABLE to learn if there were any plans to remove the injectors from the engine for reconditioning or replacement. It was thought that this would present an opportunity to determine if the suspected fueling anomalies actually did exist. Unfortunately, this maintenance work was not scheduled for the immediate future, but the E.O. did agree to make exhaust pyrometer readings for the individual cylinders under steady-state conditions during the next patrol. These readings were duly received, but efforts to correlate them in any diagnostically meaningful way with the ICAV data proved futile; they neither contradicted nor reinforced our speculations about the ALCO engine's condition.

Figure 5.11 (Traces 19 and 21) shows ICAV for no-load operation at 700 RPM. The higher engine speed results in a "bunching up" of the

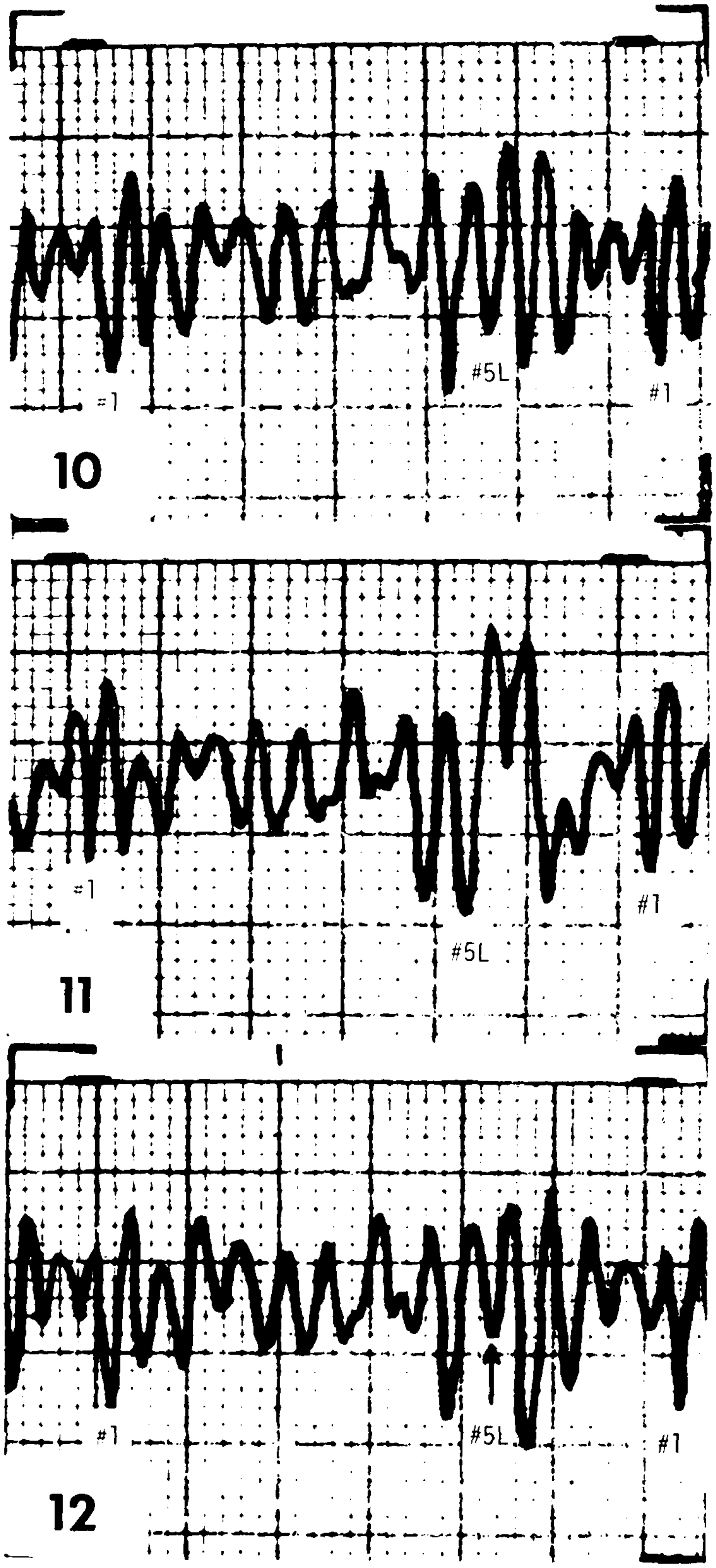


NORMAL FUEL RACK SETTING,
16-85 Hz Bandpass

OVERFUEL CONDITION,
16-86 Hz Bandpass

UNDERFUEL CONDITION,
16-85 Hz Bandpass

FIGURE 5.7 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 5L, UNDER LOAD AT 435 RPM

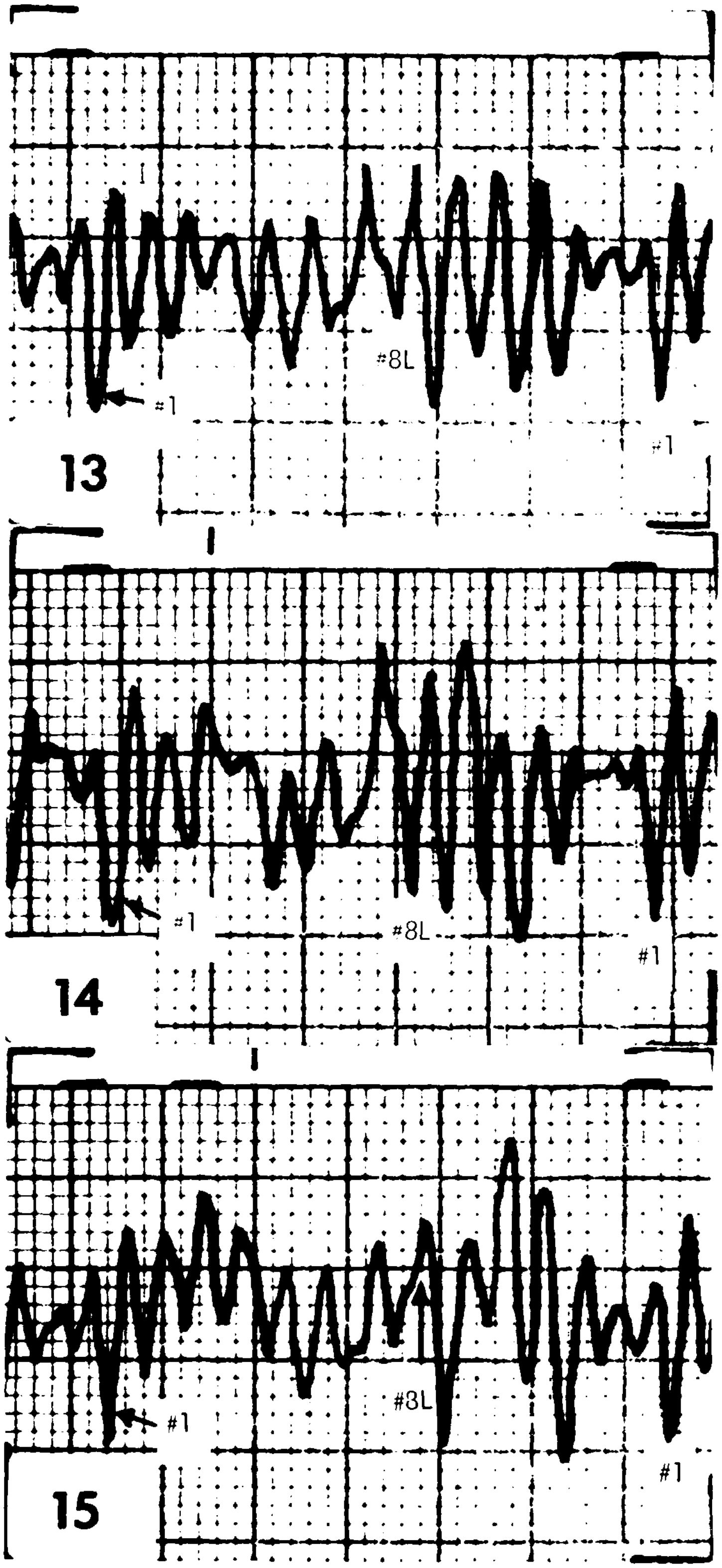


NORMAL FUEL RACK SETTING,
16-85 Hz Bandpass

OVERFUEL CONDITION,
16-85 Hz Bandpass

UNDERFUEL CONDITION,
16-85 Hz Bandpass

FIGURE 5.8 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 5L, NO-LOAD OPERATION AT 435 RPM

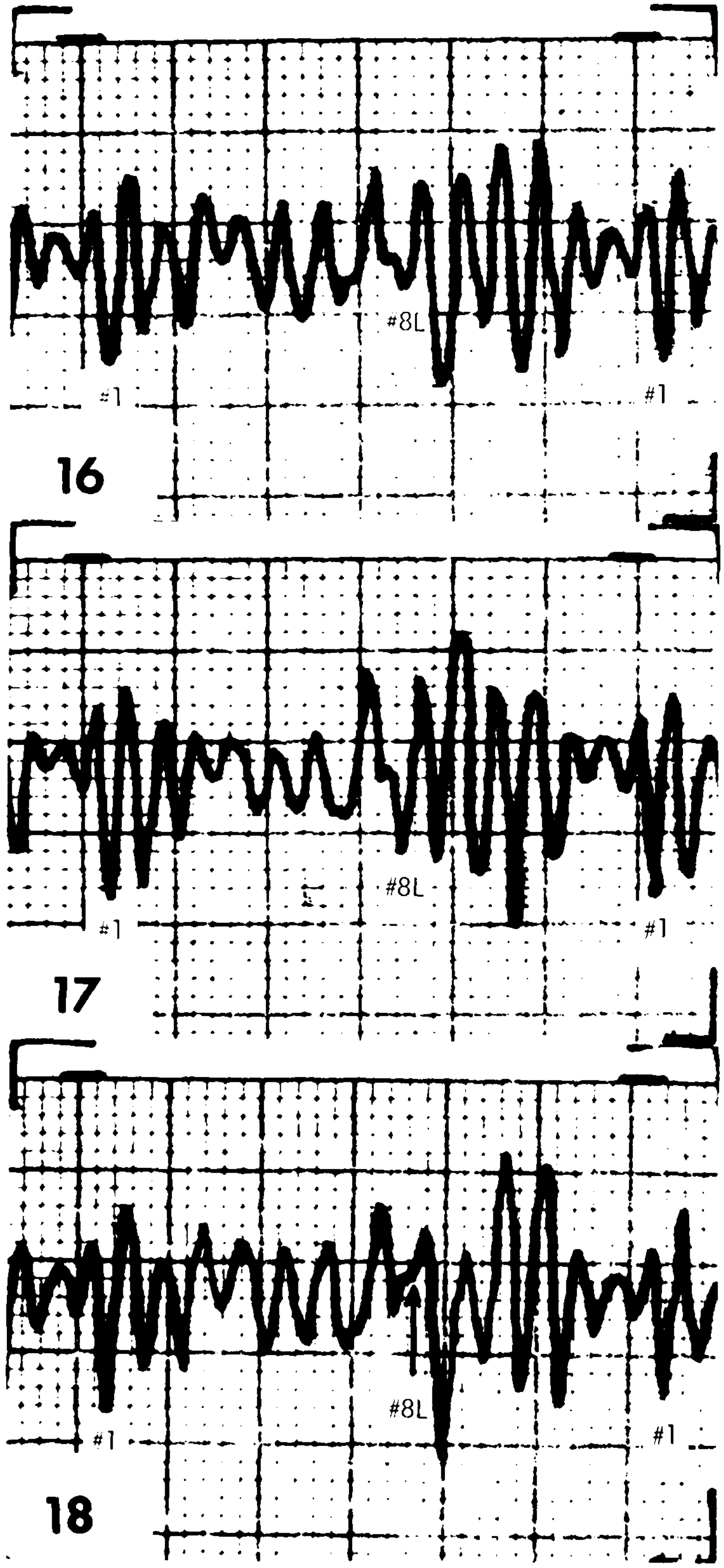


NORMAL FUEL RACK SETTING,
16-85 Hz Bandpass

OVERFUEL CONDITION,
16-85 Hz Bandpass

UNDERFUEL CONDITION,
16-85 Hz Bandpass

FIGURE 5.9 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 8L, UNDER LOAD AT 435 RPM

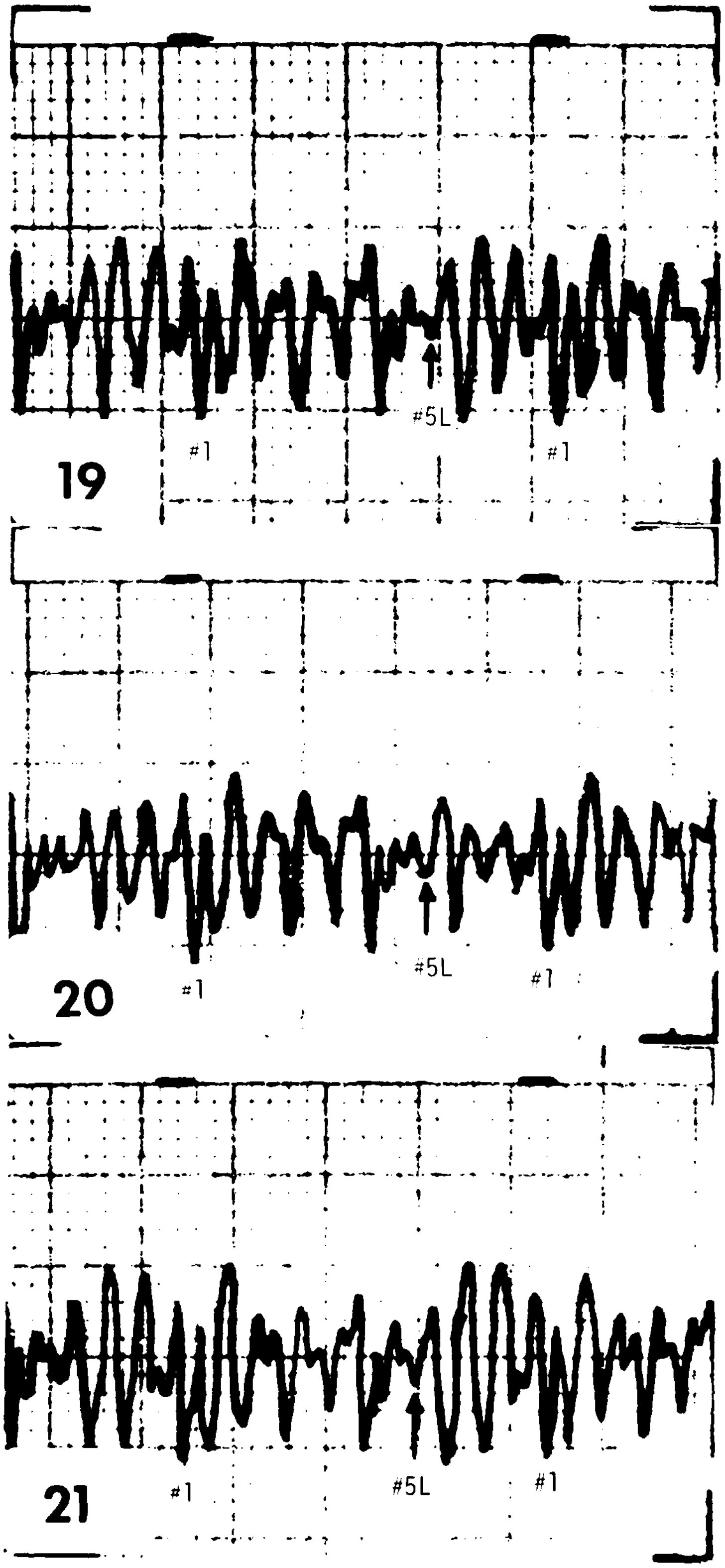


NORMAL FUEL RACK SETTING,
16-85 Hz Bandpass

OVERFUEL CONDITION,
16-85 Hz Bandpass

UNDERFUEL CONDITION,
16-85 Hz Bandpass

FIGURE 5.10 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 8L, NO-LOAD OPERATION AT 435 RPM



NORMAL FUEL RACK SETTING,
75-110 Hz Bandpass

OVERFUEL CONDITION,
75-110 Hz Bandpass

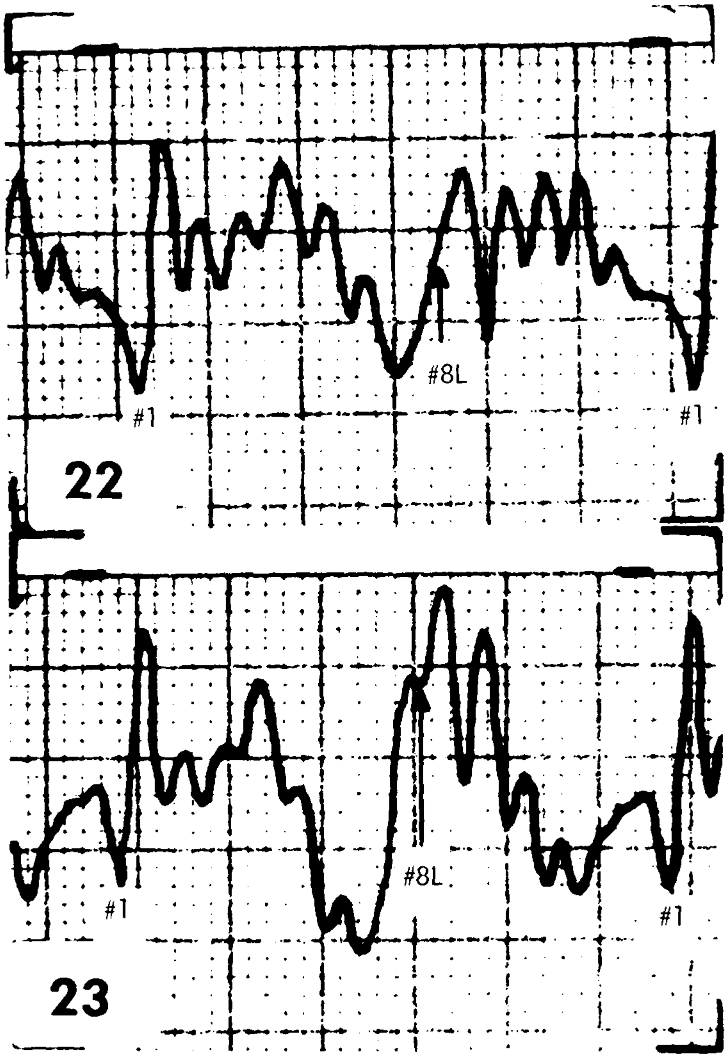
UNDERFUEL CONDITION,
75-110 Hz Bandpass

FIGURE 5.11 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 5L, NO-LOAD OPERATION AT 700 RPM

individual power impulse peaks and a corresponding loss in definition. However, careful inspection of the traces reveals that all 16 peaks are present, and the suspected fueling imbalances in the middle and toward the end of the firing order are still in evidence. The induced fueling imbalance in Cylinder 5L did not result in as obvious a change in the waveform as it did at the lower engine speed. Operating the engine with this defect and under load at this speed would probably have resulted in greater definition in the waveform, but loaded operation was not feasible at dockside, as was mentioned before. In any case, we were prepared for a much greater degradation in signal quality at the higher-speed condition, and these results were deemed encouraging under the circumstances.

The ICAV data in Figure 5.12 (Traces 22 and 23) were obtained during the period of initial check-out following installation of the test equipment. In fact, the bandpass width (10-50 Hz) employed during these tests is substantially different from that used in the tests for record at 435 RPM. The reason for including these traces here is that after they were made--and before the tests for record were run--it was discovered that the bolt which connects the injection pump rack for Cylinder 8L to the governor control rod was loose, which caused the rack to operate in an abnormal manner. The fact that the peak for this cylinder is missing in the baseline run (Trace No. 22) indicates that the cylinder was operating with an underfuel condition. This conclusion is supported by data obtained with induced overfuel (Trace No. 23); it can be seen that the overfuel resulted in only a slight peak in the waveform for this cylinder. While this mechanical problem may not be common for these engines, the ICAV signal did in fact show that the problem existed.

Figure 5.13 presents the only dynamic crankcase pressure data obtained during these tests. The pulsations recorded are of small amplitude and very close together, and the enhancement and enlargement processes did not materially improve the situation. The low amplitude of the signals was surprising since similar measurements with the Enterprise engine at SwRI produced signals of a size suitable for ready interpretation. It was subsequently discovered that the use of the ALCO dipstick tube as the pressure port may have caused this problem (though this is common practice on smaller engines that we have tested) since it appears that the crankcase end of the tube is normally below the lubricant level. This condition would dampen the pressure pulses, and sloshing of oil in the crankcase could have introduced extraneous peaks in the signal. Amplification of the pressure signal might have alleviated some of the difficulties, but provision for amplification had not been made because of the transducer's adequate performance with the Enterprise test engine.



LOOSE RACK, OTHERWISE NORMAL INJECTION PUMP OPERATION
10-50 Hz Bandpass

LOOSE RACK WITH INTENTIONAL OVERFUEL CONDITION INDUCED
10-50 Hz Bandpass

FIGURE 5.12 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING (LOOSE RACK) IN CYLINDER NO. 8L, NO-LOAD OPERATION AT 435 RPM

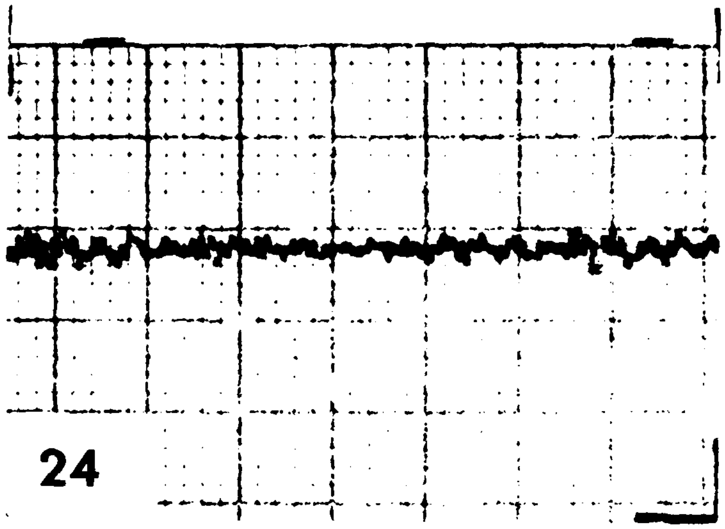


FIGURE 5.13 - DYNAMIC CRANKCASE PRESSURE PULSATIONS FOR ALCO ENGINE IN NORMAL CONDITION, NO-LOAD OPERATION AT 435 RPM

Figure 5.14 presents a selection of the ICAV data just discussed in composite form with explanatory captions so that ready comparisons may be made between the various ICAV records produced by varying engine operating conditions.

5.2.3 Conclusions

We may conclude from the data in this section that:

- The same ICAV techniques developed and tested on the Enterprise engine appear to be applicable to the ALCO 251 as installed in the WMEC DURABLE; however, signal quality (that is, the change in ICAV signal vs. fuel change, and regularity of the waveform peaks) is much poorer than on the smaller test engines (including the Enterprise) employed during other test series.

- The ICAV signals look significantly different from all earlier ones. The reduced signal amplitude for some sequences of cylinders could not be fully explained. It is unlikely that a complete group of injectors or pumps would all be defective, and that explanation now appears to be rather tenuous.

- PKD data were not suitable for ready interpretation.

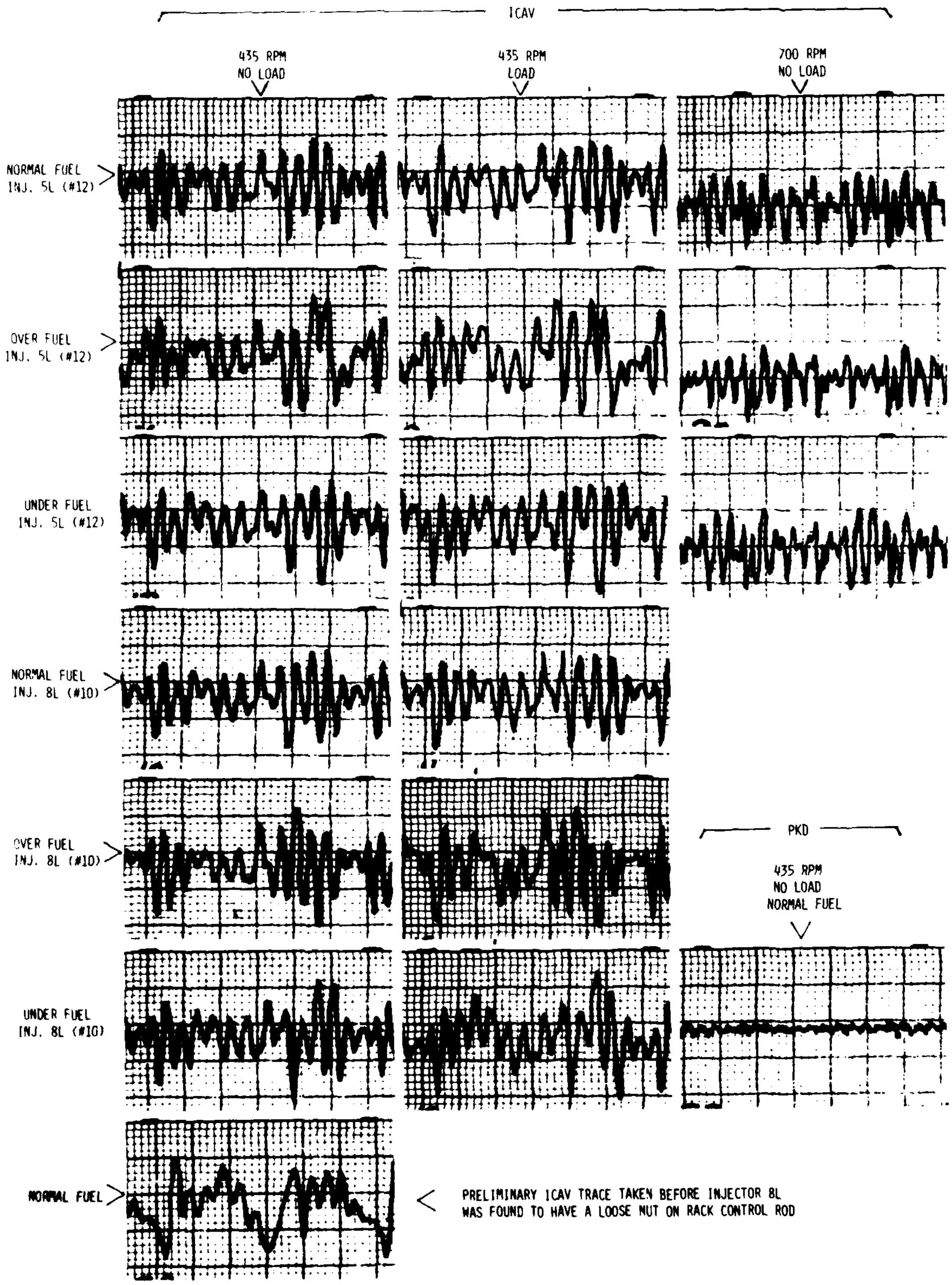


FIGURE 5.14 - DATA MATRIX FOR ALCO 16V 251B (STARBOARD) ENGINE
USCGC DURABLE (WMEC 628)

5.3 ALCO 16V 251B Test Engine at ALCO Plant

5.3.1 Test Procedures

Test methods followed with this engine generally paralleled the procedures outlined in Section 5.2, with certain additions. By fabricating a special adapter, we were able to mount the shaft encoder at the rear of the alternator which is attached to (and driven by) this test bed engine. SYNCH was by means of a sensor on the No. 1 cylinder's injection line. PKD was sensed from a port above oil level in the crankcase, and ladder tape was installed on the flywheel as described earlier. Fueling defects were induced by manipulation of a specific injector rack and, in addition, a crankcase leakage or blowby defect was induced by removal of three of the five piston rings in one cylinder. Magnetic tape recordings, as well as direct hard-copy chart recordings, were made of all signals.

Measurement of engine ICAV during these tests was plagued by two problems, neither of which was unexpected. First, the instrumentation picked up considerable electrical noise from the multitude of electrical components in the test cell. Since we had been warned in advance by ALCO about this problem, we took the precaution of utilizing shielded cable for all SwRI instrumentation and of being very particular with grounding points. Once a usable signal-to-noise ratio had been obtained, the second problem became apparent: the large (about 3400 Kg) rotating mass of the alternator attached directly to the engine flywheel caused the variation in crankshaft angular velocity to be, for all practical purposes, non-existent. In other words, compared to a ship's propulsion engine, this test engine had several times the flywheel mass of a shipboard installation. Repeated attempts to measure ICAV confirmed that the instrumentation was functioning with normal sensitivity, but that there was no detectable variation in the angular velocity of the rotating assembly. This is, of course, the result of very good matching between the engine and alternator for this particular installation, and it effectively prevented usable ICAV measurements from being made. The risk associated with attempting to utilize a test bed engine in a configuration not in every way equivalent to the ship propulsion installation was understood from the beginning, but since a similar arrangement (the Enterprise engine at SwRI) had yielded promising results, the risk was deemed acceptable. However, the ratio of rotating mass to firing impulses per revolution was simply too great (very small K-factor) in this test engine for it to yield usable ICAV data.

The third problem encountered involved our attempts to measure PKD. It was possible to obtain a waveform which appeared to correspond to the pressure pulsations normally present in the engine crankcase. However, the very sensitive pressure transducer apparently registered the acoustical noise associated with each cylinder firing event in lieu of (or in addition to) the crankcase pressure pulsations. This condition was determined by placing a valve in the line between the crankcase and the transducer and conducting tests with the valve opened and closed. The waveforms thus recorded were essentially identical at many test conditions.

Even though the calibration and baseline data runs had disclosed the difficulties enumerated above, it was decided to obtain data for record with induced leakage defects as noted above and see if careful analysis would yield answers which would be of benefit in later test work.

5.3.2 Data Analysis

The ICAV and PKD obtained in these tests were not of usable quality for the reasons given above. However, a careful review of all instrumentation and procedures employed in the test program at ALCO was conducted to determine if any steps could be taken to help ensure success of the next scheduled series of tests at Fairbanks Morse since that engine was configured much the same as the ALCO.

It was concluded that the Mk II ICAV instrument was sensitive enough to measure ICAV under normal circumstances since the earlier Mk I instrument was able to detect ICAV during the test program conducted on the medium-endurance cutter DURABLE, yet the Mk II had demonstrated by comparison better dynamic range and sensitivity than Mk I. Thus, the configuration encountered with the ALCO test engine described above was indeed the reason that the ICAV signal proved too weak for diagnostic use. The same difficulties were now anticipated for the upcoming test series with the Fairbanks Morse test bed engine, which is discussed in the following section.

Even though instrumentation had been shown adequate to measure ICAV of a shipboard installation, it was apparent that an extensive instrument redesign effort would be required to increase sensitivity to the point where the very low-level ICAV signals produced by these non-propulsion (test bed) engines could be detected, and even then the signals would require further processing to be useful. Such an effort was outside project objectives.

The dynamic crankcase pressure data recorded as hard-copy during the tests revealed that pressure pulsations due to blowby from a known defect could not be detected by inspection of the traces. This meant that either significant blowby was not produced by the simulated malfunction in one cylinder or that the pressure pulsations, though present, were damped or masked so as not to appear in the recorded signal. The least desirable situation would be that the pressure pulsations were indeed present, but were not seen by the transducer. We therefore analyzed this possibility.

It was speculated that the pressure pulsations might have been damped by the crankcase baffles used to reduce oil splash since the transducer pressure port was several feet away from the cylinder with the induced defect. But to be a practical diagnostic measurement, the transducer must pick up pulsations from any cylinder, regardless of its proximity to the pressure port; otherwise, a transducer would have to be installed near each cylinder or pair of cylinders, an impractical solution from the standpoint of quick transducer installation and data acquisition.

Therefore, if this was the problem, it imposes a limitation on the use of PKD as a diagnostic parameter that changes in the transducer and/or signal conditioning will not alleviate.

The second possible reason for lack of a definite pressure pulse in the waveform was alluded to earlier: i.e., that acoustical noise registered by the transducer interfered with the pressure pulse due to gas leakage into the crankcase. This possibility was rejected because a transducer of adequate sensitivity will always register some acoustical noise, but suitable filtering of the signal to separate noise from the pressure pulsation is quite straightforward and has always proven practical in past work with small, high-speed engines. The pressure change due to the defect consists of much lower frequency components than combustion or mechanical noise and can therefore be isolated by transducer and signal conditioning design.

5.3.3 Conclusion

We conclude from the above that:

- ICAV is not a practical diagnostic tool for engines which are permanently attached to large rotating masses (cannot be declutched), since the K-factor is too small in a properly designed engine installation.

- PKD from a single pressure port in the crankcase of large engines of the ALCO type will probably be limited to detection of gross defects because of the crankcase baffling employed.

- Caution should be used in attempting to extrapolate diagnostic data and test techniques from one class of engine, or one type of engine installation, to another.

5.4 Fairbanks Morse Eight-Cylinder 38D8-1/8 Test Engine at FM Plant

5.4.1 Test Procedures

The shaft encoder used in the ALCO tests (Section 5.3) was reworked to fit the rear of the alternator shaft driven by this engine (which was configured almost exactly like the ALCO). The same test difficulties were expected, but it was decided to pursue program objectives with this engine anyway. Regarding use of the shaft encoder, it was anticipated that even if we were successful in using it to detect ICAV signals for this engine, it would still not be clear just how useful such data would be in terms of achieving program objectives since it could not be used on-board a ship.

Specifically, the reasons for conducting tests at the engine manufacturers' facilities with test bed engines in the first place was to obtain the most suitable baseline engine (i.e., an engine in known good

condition) and, hence, to obtain a better definition of the relationship between a known induced malfunction and the resulting change in the ICAV signal. If variations in flywheel angular velocity of the FM engine, when sensed by ladder tape and scanner, turned out to be so small as to escape detection, then the major objective of the test bed work would still remain unfulfilled, and it was not thought that acquisition of ICAV data from another type of transducer (the shaft encoder) located on a different part of the engine would help to salvage the situation. The only reason for attempting to obtain ICAV data with the shaft encoder was to use these data as a reference or bench mark for comparison with data obtained by the ladder tape/scanner technique since, theoretically, the shaft encoder should offer slightly superior resolution. Otherwise, test procedures were essentially the same as those used at the ALCO plant.

Due to its design, which features cylinder liners with ports at both ends, PKD defects cannot be induced into the FM opposed-piston engine short of actually perforating a piston. The ports allow pressure pulsations from piston ring leakage to enter either the intake air receiver or the exhaust manifold, but not the upper or lower crankcase.

5.4.2 Data Analysis

The FM engine produced ICAV signals which were just barely identifiable as belonging to a specified cylinder. They were, however, like the factory ALCO data, i.e., much too poor in quality to consider for diagnostic use. Therefore, they are not reproduced here. The reasons for this condition were, again, too much rotating mass attached to the engine and no way to declutch the alternator to reduce this mass.

5.4.3 Conclusions

From these tests we conclude that:

- Large diesel engines in this configuration cannot be diagnosed with ICAV, and the same considerations apply as in the case of the factory ALCO tests described in the previous section.

- PKD can only respond to holes in a piston. Leakage past the rings goes into either the exhaust manifold or the air box, and not into the crankcase; pressure pulses cannot, therefore, be detected with the engine geometry of the FM opposed-piston power plant. Implementing an artificial defect of this type was considered too dangerous to attempt in light of its limited relationship to defects that actually occur.

As part of the trip to FM a visit was made to the U.S. Navy Propulsion Engineering School at Great Lakes, Illinois. We had been advised that this facility had both ALCO 16-251 (turbocharged) and Fairbanks Morse 38D8-1/8 (non-turbocharged) test bed engines connected to water brake dynamometers, and this proved to be true. This was potentially a much more

desirable test configuration than the engines at either ALCO or Fairbanks Morse with their large alternators of considerable rotating mass. This visit ultimately resulted in the test series described in the next two sections.

5.5 ALCO 16V 251C (Clockwise/Opposite Rotation) Engine at Great Lakes Naval Training Center

5.5.1 Test Procedures

The ALCO engine test series conducted at the U.S. Navy Propulsion Engineering School facilities at Great Lakes, Illinois, were patterned after those conducted at the engine manufacturer's facilities, but utilized an engine connected through a clutch to a water brake dynamometer. Normal engine PKD was examined, but we were not allowed to induce crankcase leakage defects into the engine. Several ladder tape tracks were emplaced and, after comparing the signals obtained from each, we settled on the so-called narrow spacing as before. SYNCH was derived from the No. 1 cylinder injector line. Data recording was by magnetic tape (later transcribed out at a slower speed in the laboratory as described earlier) and by oscilloscope photographs.

5.5.2 Data Analysis

This ALCO engine produced ICAV signals that were similar to those obtained on the cutter DURABLE; however, the waveforms were not as consistent with regard to the effect of underfuel and overfuel conditions as was the case for the earlier data. Lack of exact knowledge about the mechanical condition of the test engine also posed a problem in interpreting the data, but the situation was even more uncertain than in the DURABLE tests since the Navy engine is used for student training and is not run under load to any appreciable extent. Therefore, even basic performance data (e.g., exhaust temperatures) were not available.

The test schedule followed during these tests is shown (with appropriate remarks) in Table 5.2. Notice that for a number of test conditions the ICAV signal filter was set to pass only very low frequency components of angular velocity change. Even though a single defective cylinder is difficult to locate when analyzing these signals (which are dubbed "N/60 ICAV" for convenience), the signals are a very sensitive indicator of power imbalance. By studying N/60 ICAV we were able (as shown later) to gain some insight into the problems which had been plaguing the large engine test series from the start.

For ease of comparison, portions of both the regular and N/60 ICAV data were extracted and made into montages (Figures 5.15 and 5.16). (Figure 5.16 also displays normal engine PKD at no-load and half-load conditions.) This presentation allows a direct and more easily understood comparison of how the ICAV signals varied as engine defects were introduced. Recall that increasing angular velocity is <u>UP</u> in these ICAV

TABLE 5.2 - DIAGNOSTIC EVALUATION OF ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER

PROJECT: 11-4132-005
DATE: 7/19/78

f_oICAV = 2/15 RPM

Test Seq.	RPM	f_oICAV	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
1	400	53	35/85	X100	0	Normal	1	50mV	----	Dyno clutched in at all times & load varied as shown.
2	400	53	35/85	X100	1/2	Normal	2	50mV	----	
3	400	53	35/85	X100	Full	Normal	3	50mV	----	
4	400	53	35/85	X100	0	Under fuel	4	50mV	----	Fuel changed by hand from approx. -80% to 40%.
5	400	53	35/85	X100	0	Over fuel	5	50mV	----	
6	400	53	35/85	X100	1/2	Under fuel	6	50mV	----	Engine has a distinct leaking sound at load.
7	400	53	35/85	X100	1/2	Over fuel	7	50mV	----	
8	400	53	35/85	X100	Full	Under fuel	8	50mV	----	
9	400	53	35/85	X100	Full	Over fuel	9	50mV	----	
10	400	53	35/85	X100	0	Normal	10	50mV	----	
11	400	53	35/85	X100	Full	Normal	11	50mV	----	
12	400	53	35/85	X100	0	Normal	12	0.1V	----	7/10/78 Dyno clutched in 21 (5 in order) and for all fuel .
13	400	53	35/85	X100	1/2	Normal	13	0.1V	----	PKD Transducer on 5L door.
14	600	53	65/140	X100	1/2	Normal	14	0.1V	----	PKD

TABLE 5.2 - DIAGNOSTIC EVALUATION OF ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER (CONT'D)

Test Seq.	RPM	f_oICAV	Filter	Gain	Load	Engine Cond	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
15	600	53	65/140	X100	0	Normal	15	0.1V	----	PKD
16	400	53	35/85	X100	1/2	Normal	16	50mV	Reel 2 000-500	ICAV estimated to be near prop curve load for 400 RPM.
17	---	--	-----	----	----	------	17	50mV	----	Pic 17 taken from recorder playback of seq. 16 - looks OK.
18	400	53	35/85	X100	1/2	Under fuel	18	50mV	500-700	
19	400	53	35/85	X100	1/2	Over fuel	19	50mV	700-900	
20	400	N/60 6.6Hz	2/10	X100	1/2	Over 5mm	20	50mV	900-1000	N/60 Component Turbo working very poorly - apparently causes wide excursions in baseline as it surges.
21	400	N/60 6.6Hz	2/10	X100	1/2	Normal	21	50mV	1000-1100	N/60 Component
22	400	N/60 6.6Hz	2/10	X100	1/2	Under -5mm	22	50mV	1100-1200	N/60 Component
23	400	N/60 6.6Hz	2/10	X100	1/2	Normal	23	50mV	----	N/60 Component
24	400	N/60 6.6Hz	2/10	X100	1/2	Over fuel 2mm	24	50mV	----	N/60 Component
25	400	N/60 6.6Hz	2/10	X100	1/2	Under fuel -2mm	25	50mV	----	N/60 Component
26	375	N/60 6.6Hz	2/10	X100	0	Normal	26	50mV	----	N/60 Component Turbo not spinning.
27	375	N/60 6.6Hz	2/10	X100	0	Over fuel 2mm	27	50mV	----	N/60 Component Turbo not spinning.

TABLE 5.2 - DIAGNOSTIC EVALUATION OF ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER (CONT'D)

Test Seq.	RPM	f_0 ICAV	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
28	375	N/60 6.6Hz	2/10	X100	0	Under fuel -2mm	28	50mV	----	N/60 Component Turbo not spinning.
29	600	----	65/140	X100	0	Normal	29	0.1V	----	PKD Transducer on 1L door.
30	600	----	65/140	X100	1/2	Normal	30	---	----	
31	600	----	65/140	X100	Full	Normal	31	---	1200-1280	Load dropped off during tape run.
32	600	----	65/140	X100	0	Normal	32	---	1280-1400	
33	400	----	65/140	X100	0	Normal	33	---	1400-1500	
34	400	53	35/85	X100	1/2	Leaking in 2L	34	50mV	Reel 3 000-400	Defective nozzle tip installed in 2L(5) 9X325X1450 ADL-145TM-836-6 Alco Fact.
35	400	N/60 6.6Hz	2/10	X100	1/2	Leaking in 2L	35	50mV	----	
36	400	53	35/85	X100	1/2	Plugged noz. in 2L	36	50mV	400-800	Def. noz. approx. 1/2 holes plugged (2 pics) firing intermittently (in 2L).
37	400	N/60 6.6Hz	2/10	X100	1/2	Plugged noz. in 2L	37	50mV	----	Recording of both 36 & 37 (last few feet shutdown).
38	400	53	35/85	X100	1/2	Eroded tip in 2L	38	50mV	800-1000	Def. Noz. eroded tip 2L(5).
39	400	N/60 6.6Hz	2/10	X100	1/2	Eroded tip in 2L	39	50mV	1000-1130	
40	400	53	35/85	X100	1/2	Normal	40	50mV	1200-1300	Baseline after return to original configuration.
41	400	53	35/85	X100	1/2	Under fuel	41	50mV	1300-1350	6L inj. fuel by hand, 11th in firing order, very bad.

TABLE 5.2 - DIAGNOSTIC EVALUATION OF ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER (CONT'D)

Test Seq.	RPM	f_oICAV	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
42	400	53	35/85	X100	1/2	10 Over fuel	42	50mV	1350-1400	6L (11th in order) appears to be worst cylinder on engine.
43	400	53	35/85	X100	1/2	Under fuel	43	50mV	1400-1450	7L inj. varied fuel by hand, 13th in firing order.
44	400	53	35/85	X100	1/2	Over fuel 10	44	50mV	1450-1500	7L inj. varied fuel by hand, 13th in firing order.
45	400	53	35/85	X100	1/2	Normal	45	50mV	Reel 4 000-200	7/11/78, 6L inj. repaired, engine exercised, runs much better.
46	400	53	35/85	X100	5/8	Normal	46	50mV	----	6L inj. was defective, bad dribble.
47	400	53	35/85	X100	1/2	Normal	47	50mV	----	Remove 8R inj. for test, coked, but cracking OK, 2L (5th for timing).
48	400	53	35/85	X100	1/2	Normal	48	50mV	----	1L (1st in order) for timing, optical pick-up moved approx. 50 later in rotation.
49	400	53	35/85	X100	1/2	Under fuel 2L	49	50mV	----	
50	400	103	93/108	X100,X50	1/2	Normal	50	0.2V	200-400	PKD 1 crankcase door.
51	400	103	93/108	X100,X50	0	Normal	51	0.2V	400-600	PKD 1 crankcase door.
52	400	103	93/108	X100,X20	1/2	Normal	52	0.1V	600-800	PKD 5 CC door (note gain change).
53	400	103	93/108	X100,X20	0	Normal	53	0.1V	800-1000	PKD 5 CC door (note gain change).
54	400	103	93/108	X100,X20	1/2	Over fuel 3L	54	0.1V	----	PKD 5 CC door (note gain change).
55	400	103	93/108	X100,X20	1/2	Under fuel 3L	55	0.1V	----	PDK 5 CC door (note gain change) (3L is 3rd in order).

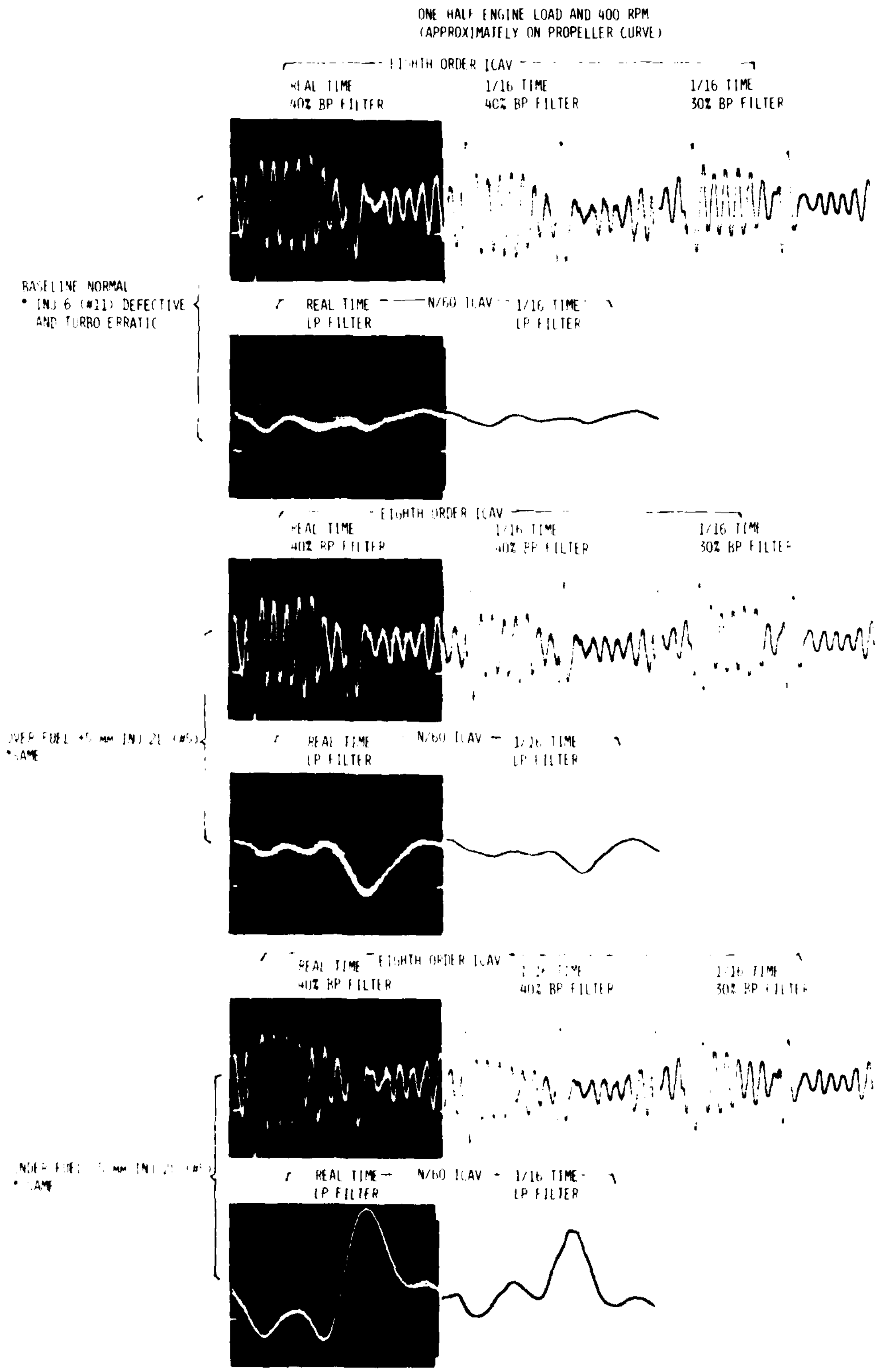


FIGURE 5.15 - DATA MATRIX FOR ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER

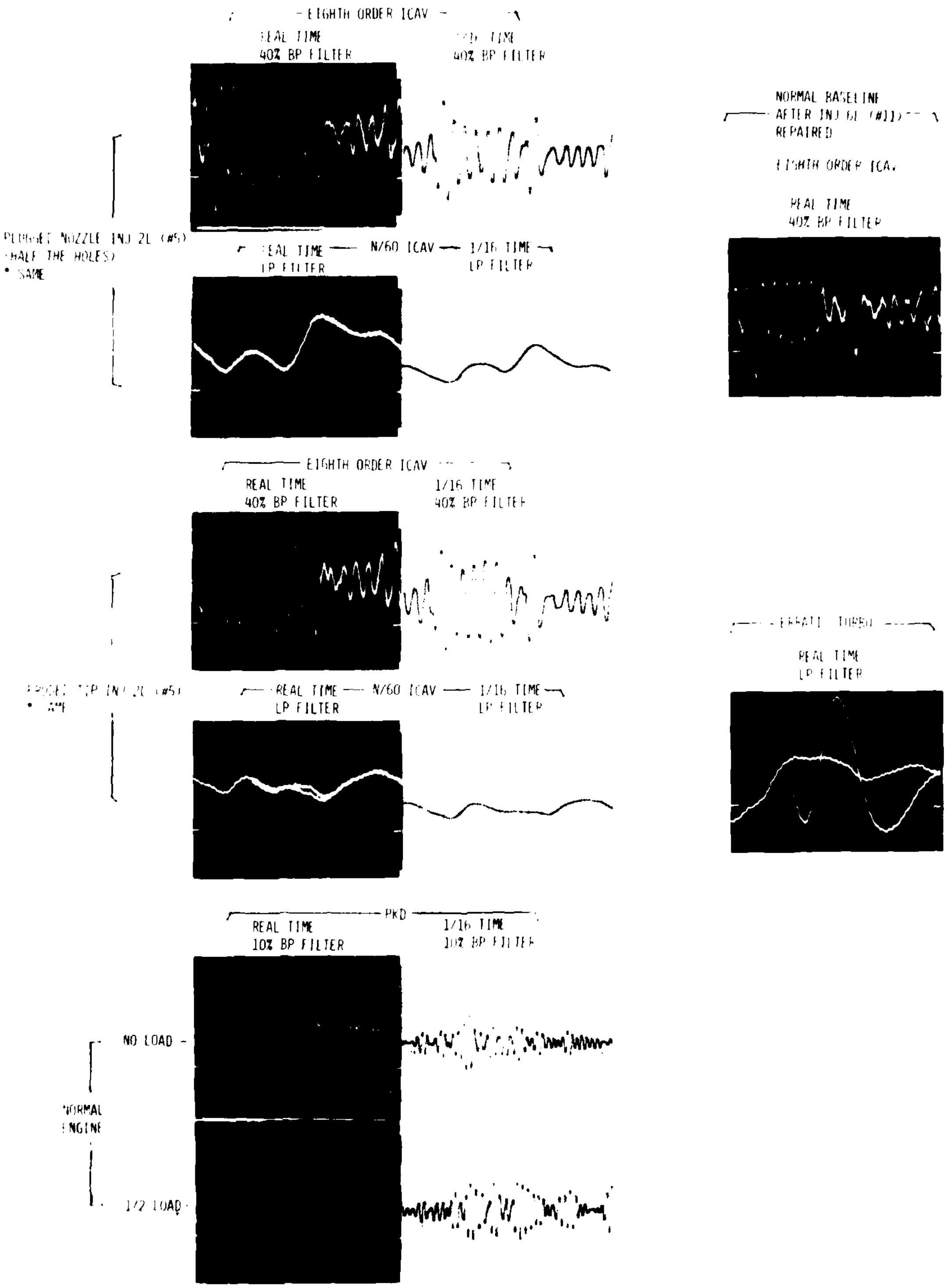


FIGURE 5.16 - DATA MATRIX FOR ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER (CONCLUDED)

traces since the Mk II detector was used. All pertinent information appears in the captions of each figure. The very large excursions in these traces are an artifact of the ladder tape splice and should be ignored.

5.5.3 Conclusion

- Although changes in the ICAV record due to misfueling and the resultant cylinder power imbalance were present, no significant improvement over results of the shipboard tests (the DURABLE series) was shown.

- The PKD waveform was undecipherable due to the presence of a great many pressure pulsations of varying amplitude, shape, and spacing. The unknown mechanical condition of this engine's pistons, rings, and cylinder liners made correlation of these crankcase pressure pulsations impossible.

5.6 Fairbanks Morse 10-Cylinder 38D8-1/8, Great Lakes Naval Training Center

5.6.1 Test Procedures

Test procedures for this engine were unchanged from those described in earlier sections of the report. Fueling defects were introduced by manipulating racks of the two injectors for the target cylinder. This engine was an old model partially modified to ND type (different pistons), but it was still very similar to the engine described in Section 5.4 except for having ten rather than eight cylinders. It was set up for direct reversing, but was operated only in right-hand (normal) rotation. The test sequence is detailed in Table 5.3, following. PKD was not measured for the reasons mentioned previously (Section 5.4.1) relating to the design of the opposed-piston FM engine.

5.6.2 Data Analysis

Figure 5.17 is a montage which illustrates with appropriate captions the principal features of the ICAV data obtained from this engine. The signals are of good quality, and definite waveform changes occur with fueling imbalance in one cylinder. The difficulty is that there appears to be no ready way to interpret the traces in terms of past experience with engines of more conventional geometry (i.e., engines not of opposed-piston design). Notice that the ICAV traces change shape radically as engine speed changes. This effect is surely due to the interplay of the torsional resonances of the engine's two crankshafts and their coupling shaft and gearing. This situation is further complicated by the fact that there is some 12° of angular timing displacement between the two crankshafts (i.e., the two opposed pistons reached their respective TDC positions some 12° out of phase). The mechanical condition of this engine was not known; it may have had power imbalances before known fueling defects were added. We can say with certainty that analysis of ICAV waveforms for engines of this type will be much more complex than for engines of more conventional geometry, such as the ALCO.

TABLE 5.3 - DIAGNOSTIC EVALUATION OF FAIRBANKS MORSE 10-CYLINDER 38D8-1/8, GREAT LAKES NAVAL TRAINING CENTER

Test Seq.	Tach* RPM	f_oICAV RPM/6	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
1	400	$67H_2$	25/115	X 20	Max	Normal	1	50mV	----	First look at ICAV-seems OK, ICAV signal amplitude approximately same as splice amplitude.
2	300	50	25/85	X 20	Max	Over fuel	2	50mV	----	Only limited overfuel available-both injectors used, 4 cyl. for all fuel cond.
3	300	50	25/85	X 20	Max	Under fuel	3	50mV	----	
4	300	50	25/85	X 20	Max	Normal	4	50mV	----	
5	400	67	25/115	X 20	Max	Over fuel	5	50mV	----	Decided baseline (N/60) shift-cyl. 4 is 5th in firing order.
6	400	67	25/115	X 20	Max	Under fuel	6	50mV	----	
7	400	67	25/115	X 20	Max	Normal	7	50mV	----	
8	300	50	30/70	X100	Max	Normal	8	0.2V	0-100	(Data starts 20' into tape) all tape data on Reel 1.
9	300	50	30/70	X100	Max	Over fuel	9	0.2V	100-200	
10	300	50	30/70	X100	Max	Under fuel	10	0.2V	200-300	
11	400	67	47/87	X100	Max	Normal	11	0.2V	300-400	
12	400	67	47/87	X100	Max	Over fuel	12	0.2V	400-500	
13	400	67	47/87	X100	Max	Under fuel	13	0.2V	500-600	

*Tach was not accurate-values from scope timing show that:

300 rpm indicated was 353 rpm
400 rpm indicated was 444 rpm
500 rpm indicated was 531 rpm

TABLE 5.3 - DIAGNOSTIC EVALUATION OF FAIRBANKS MORSE 10-CYLINDER 38D8-1/8, GREAT LAKES NAVAL TRAINING CENTER (CONTINUED)

Test Seq.	Tach* RPM	f_oICAV RPM/6	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
14	500	83	60/103	X100	80%	Normal	14	0.2V	600-700	
15	500	83	60/103	X100	80%	Over fuel	15	0.2V	700-800	
16	500	83	60/103	X100	80%	Under fuel	16	0.2V	800-900	
17	500	83	60/103	X100	0	Normal	17	0.2V	900-1000	
18	400	67	47/87	X100	0	Normal	18	0.2V	1000-1100	Baselines
19	300	50	30/70	X100	0	Normal	19	0.2V	1100-1200	

*Tach was not accurate - values from scope timing show that:

300 rpm indicated was 353 rpm
400 rpm indicated was 444 rpm
500 rpm indicated was 531 rpm

ENGINE FIRING ORDERS:

1	2	3	4	5	6	7	8	9	10	
1	6	10	2	4	9	5	3	7	8	RH rotation (normal)
1	8	7	3	5	9	4	2	10	6	LH rotation (reverse)

- BOTH INJECTORS ON #4 CYLINDER (FIFTH IN FIRING ORDER) MANIPULATED TO PRODUCE SINGLE CYLINDER MISFUELING CONDITIONS
- EIGHTH ORDER ICAV WITH 30% BP FILTER

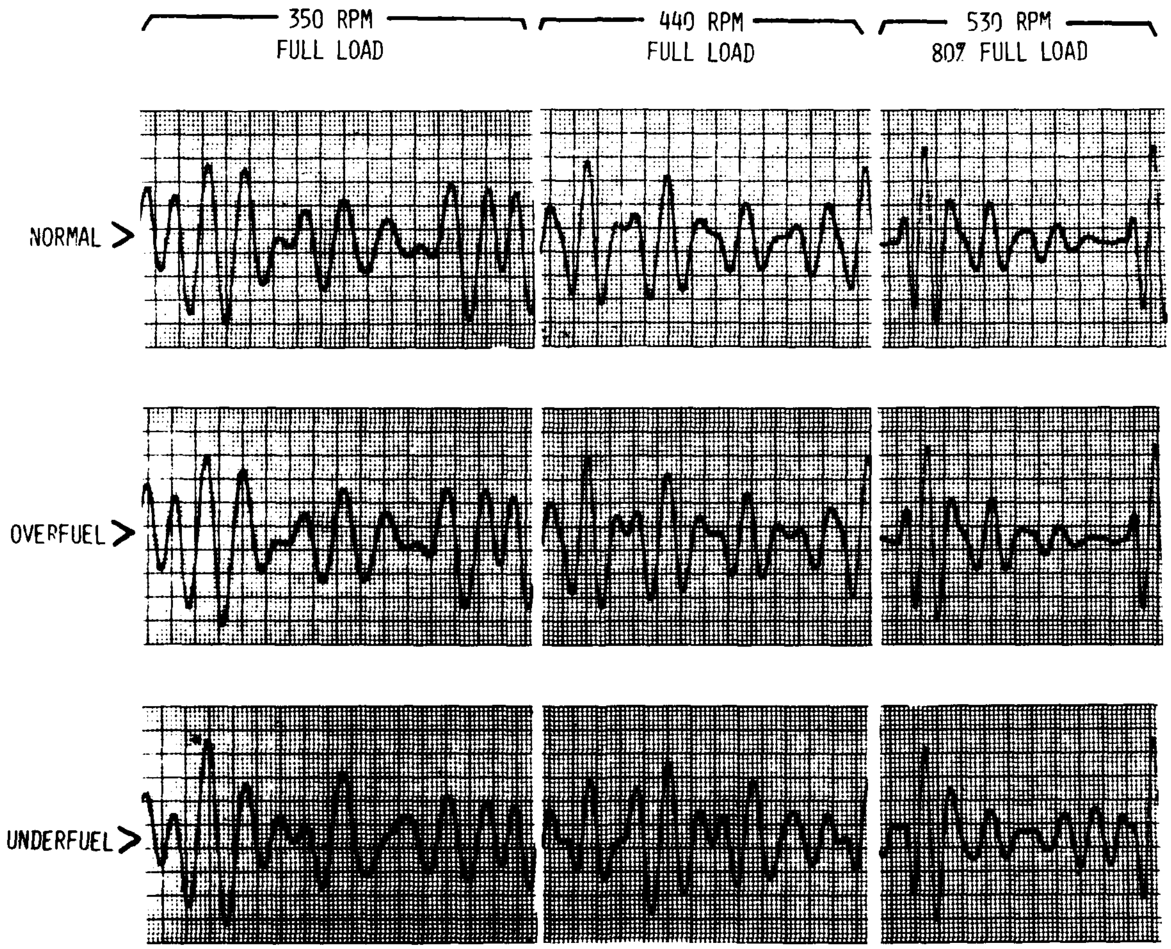


FIGURE 5.17 - DATA MATRIX FOR FAIRBANKS MORSE 10-CYLINDER 38D8-1/8, GREAT LAKES NAVAL TRAINING CENTER

5.6.3 Conclusions

We conclude from these tests that:

- Torsional resonance ICAV effects in engines of the opposed-piston type are pronounced and very complex. As in other large diesel engines, these effects preclude simple and straightforward analysis of ICAV data for diagnostic purposes.

- Since ICAV changes vs. fueling defects are demonstrated in the data, this means that in principle ICAV is a feasible diagnostic tool for these engines, but one that will require more sophisticated signal processing to yield adequate data interpretation.

5.7 ALCO 16V 251B Engines Onboard USCGC COURAGEOUS (WMEC 622)

5.7.1 Test Procedures

Tests on both main propulsion engines were accomplished during two periods. The diagnostic test equipment and its ancillary devices were set up in a clear space near the aft ends of the engines between their gear boxes. From this location it was possible to conveniently move test sensors back and forth from one engine to the other. ICAV data were first recorded (Part I, Table 5.4) while the cutter was moored at the dock with the engines declutched and unloaded (for later harmonic analysis), and subsequently (Part II, Table 5.4) loaded engine ICAV data were acquired while underway at sea. The only way to measure PKD was by means of the oil dipstick tube, no other openings into the crankcase being available. Since previous tests on the cutter DURABLE had shown this location for the transducer to be unsuitable, we made only cursory measurements to confirm that the same anomalous behavior existed for the PKD data in this case.

A significant change was made in the magnetic tape data recording technique used in these tests in that wide-band (5 Hz to 500 Hz bandpass) signal filtering was used so that when the ICAV signals were later transcribed at lower tape speed as chart traces, narrow-band selective filtering could be employed to select only the ICAV component desired (conventional ICAV, N/60 ICAV, and so on). The COURAGEOUS raw data were thus much more useful than that which had been recorded in earlier tests since that earlier data was band-limited from the start. Identical test procedures were used on both engines except as noted in the following sections.

5.7.2 ALCO 16V 251B (No. 1 Engine, Starboard side, Clockwise/Opposite Rotation)

SYNCH was obtained from the No. 1 cylinder injector line. The rack control on Cylinder 5L (No. 7 in the firing order) was manipulated to provide abnormal fueling conditions.

TABLE 5.4 — TEST SCHEDULE FOR ICAV DATA ACQUISITION, USCGC COURAGEOUS

SwRI Project 11-4132-005

USCGC "COURAGEOUS" - Port (P) #2 Engine, Standard (ccw) Rotation Alco 16V251
Stbd. (S) #1 Engine, Opposite (cw) Rotation Alco 16V251

Operating Notes: (1) Record exactly 200' of tape (15"/sec) at each condition including voice I.D. at start of each segment. This is ~ 2.6 min.

(2) On the Port (P) #2 Std. Rot. engine manipulate Inj. 6R (#7) Synch. on the 1 Right Inj. (#1 in F.O.).

(3) On the Stbd. (S) #1 Opp. Rot. engine manipulate Inj. 5L (#7).

(4) Record all signals wide band 5Hz - 500 Hz, reduce upper end cut-off frequency if have too much noise & record value. Use same band pass for all recordings.

(5) Record data only on warmed-up engine.

(6) Observe RPM in boxes OR enter proper RPM when using Bell Positions underway.

(7) Identify each test by ROW & then COL, example - Test 1E means engine #1, normal, 550 RPM.

I. Baseline Sequences: no load (declutched)

#1 Engine (Stbd)	A	B	C	D	E	F	G	H	J	K	Remarks
1 Normal	low idle	400	450	500	550	600	700	800	900	1000	
2 Underfuel	low idle	400	-	500	-	-	700	-	-	-	
3 Overfuel	low idle	400	-	500	-	-	700	-	-	-	
#2 Engine (Port)											
4 Normal	low idle	400	450	500	550	600	700	800	900	1000	
5 Underfuel	low idle	400	-	500	-	-	700	-	-	-	
6 Overfuel	low idle	400	-	500	-	-	700	-	-	-	

II. Loaded Sequences: Underway normal RPM/pitch *BP = Bell Position

#1 Engine (Stbd)	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	Remarks
7 Normal									
8 Underfuel									
9 Overfuel									
#2 Engine (Port)									
10 Normal									
11 Underfuel									
12 Overfuel									

5.7.2.1 Loaded Engine Data Analysis

The ICAV traces in Figure 5.18 were extracted from the wide-band data recorded from the No. 1 engine while underway at sea and are appropriately marked regarding operating parameters. Inspection of these data reveals that the fueling imbalances produced by manipulating the rack for No. 5L cylinder did indeed produce changes in both the normal and N/60 ICAV record. At the same time, the traces are too irregular to allow simple and straightforward defect analysis even though they were taken at optimum conditions, i.e., with the engine under load. These ICAV records are not of the quality needed to meet the primary program objective of simple interpretation by Coast Guard operating personnel. To be useful, considerable refinement in signal processing and display would be required. The lack of regularity in these ICAV traces is similar to that encountered in the earlier large engine tests and, once again, the difficulties encountered may be attributed to engine operation too near the crankshaft torsional resonance point.

5.7.2.2 Conclusions

These data reinforce the conclusions arrived at in previous tests with ICAV for large diesel engines. They are:

- Cylinder power imbalance very definitely changes the baseline (normal) ICAV record, but the changes are not interpretable in any straightforward manner due to the irregularity of the signals.
- This means that in principle ICAV is a feasible diagnostic tool for these engines, but in a context that is beyond the scope of this project; i.e., more sophisticated signal processing is required.

5.7.3 ALCO 16V 251B (No. 2 Engine, Port Side, Counter-Clockwise/Standard Rotation)

5.7.3.1 Loaded Engine Data Analysis

Fueling imbalances were induced in this engine by manipulating the rack of the No. 6 cylinder (seventh in the firing order) in the same fashion as was done for the No. 1 engine. ICAV traces for this engine are also shown in Figure 5.18, and remarks in Section 5.7.2.1 (above) also apply to this engine.

The normal fuel or baseline ICAV for Engine No. 2 is decidedly different from that of Engine No. 1. The engines employ reversed firing orders to produce standard (CCW) and opposite (CW) rotation. We now know there is a strong interaction between the crankshaft torsional resonance and the eighth-order ICAV which we are attempting to use for cylinder power imbalance diagnosis, and that this interaction is evidently quite different for the two firing orders. On the other hand, changes in

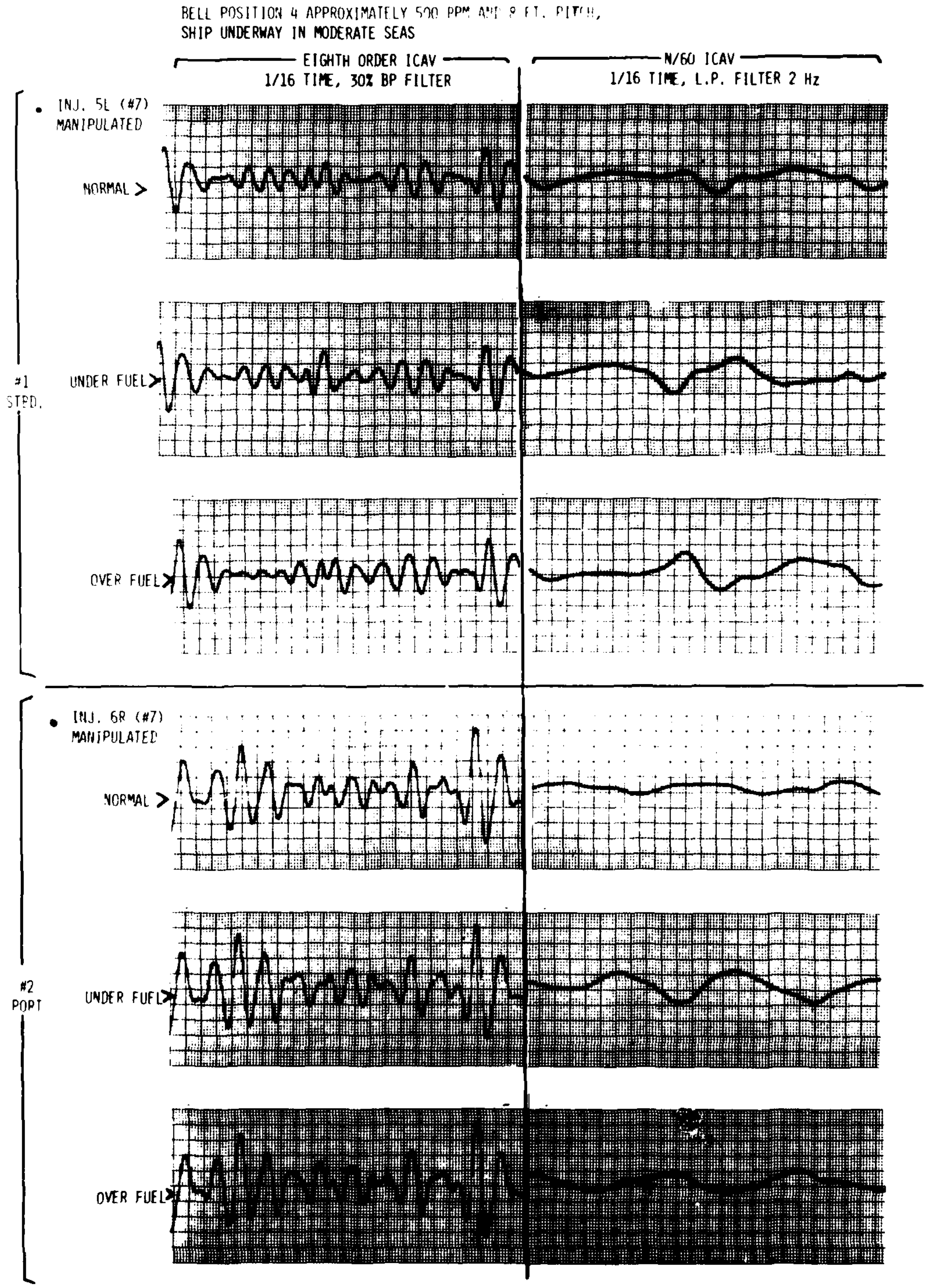


FIGURE 5.18 - DATA MATRIX FOR ALCO 16V-251B (PORT AND STARBOARD), ENGINES, USCGC COURAGEOUS), (WMEC 622)

the individual normal (baseline) ICAV as fuel imbalance (and, hence, cylinder power imbalance) is introduced appear to be of about the same relative magnitude for both engines.

5.7.3.2 Conclusions

Conclusions are the same as for Engine No. 1.

5.7.4 Analysis of Unloaded Engine Data

Part I of Table 5.4 shows the range of engine conditions over which wide-band (5 to 500 Hz bandpass) ICAV data were recorded from the unloaded main propulsion engines. Back in the laboratory the data tapes were processed with an audio-frequency spectrum analyzer, and chart recordings were made of the ICAV frequency spectrum produced at each engine test condition. A complete set of these spectra is in Appendix D.

Some of the chart recordings in Appendix D are quite noisy. This noise was a recording artifact caused by improper functioning of the instrumentation tape recorder, which was damaged in transit to the test site. Even though the tape noise was worrisome, and recorded signals were sometimes erratic, there is no reason to suspect that any other inaccuracy exists in the recorded data since the noise was definitely determined to have been caused by mechanical vibrations of faulty electrical connections inside the recorder. This means that we can reasonably expect that whenever ICAV signal data were present on the magnetic tape, it was satisfactory data. To express this a little differently, the problem was primarily dropped or missing data rather than anything being added to the ICAV signal. Fortunately, enough extra data were recorded at each engine condition to allow selection of the (relatively) cleanest portion for analysis.

Figures 5.19 and 5.20 are tracings of harmonic data for Engine No. 1 (starboard side) and Engine No. 2 (port side), respectively. These data are from the low and high ends of the engine speed range and have been corrected for baseline and frequency drift errors introduced by the spectrum analyzer equipment. Observe that they are quite similar in appearance insofar as the high-amplitude harmonic peaks are concerned. Even though there may be significant information in the many low-amplitude harmonic peaks (which are decidedly different for the two engines), we will confine our analysis to the major harmonics present and assume that anything applicable to one engine also applies to the other.

A careful examination of the high-order harmonic spectra for the two engines under conditions of over-and under-fueling at both 500 and 700 RPM does not disclose any changes which might be considered to be of diagnostic significance. This is disappointing, but it can be explained by looking at Figure 5.21 which plots in bar graph form the amplitude and frequency location of the major ICAV harmonic components up to 500 Hz at various engine speeds. It can be seen that the two major ICAV harmonics are

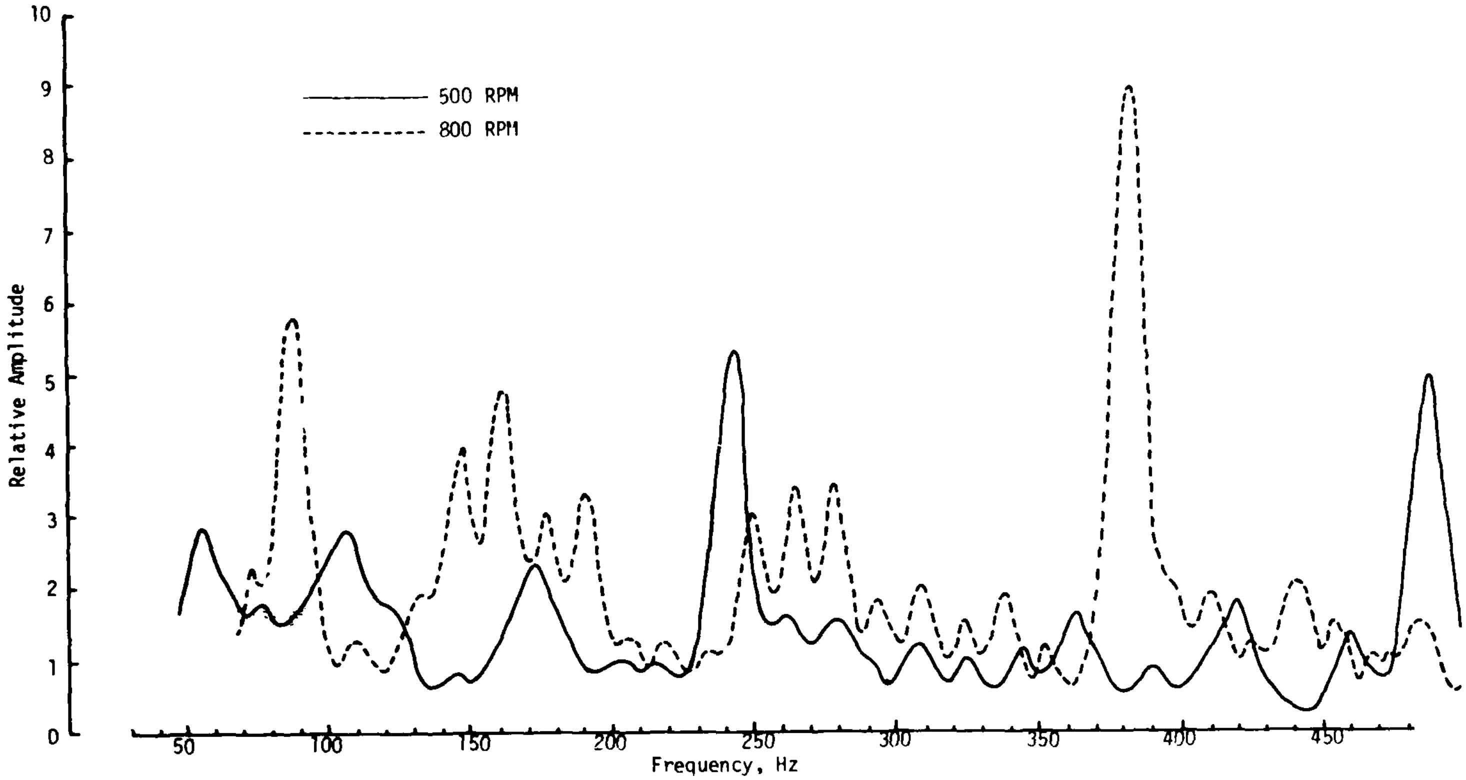


FIGURE 5.19 - HARMONIC DATA FOR USCGC COURAGEOUS, NO. 1 (STARBOARD) ENGINE UNDER NO-LOAD OPERATION

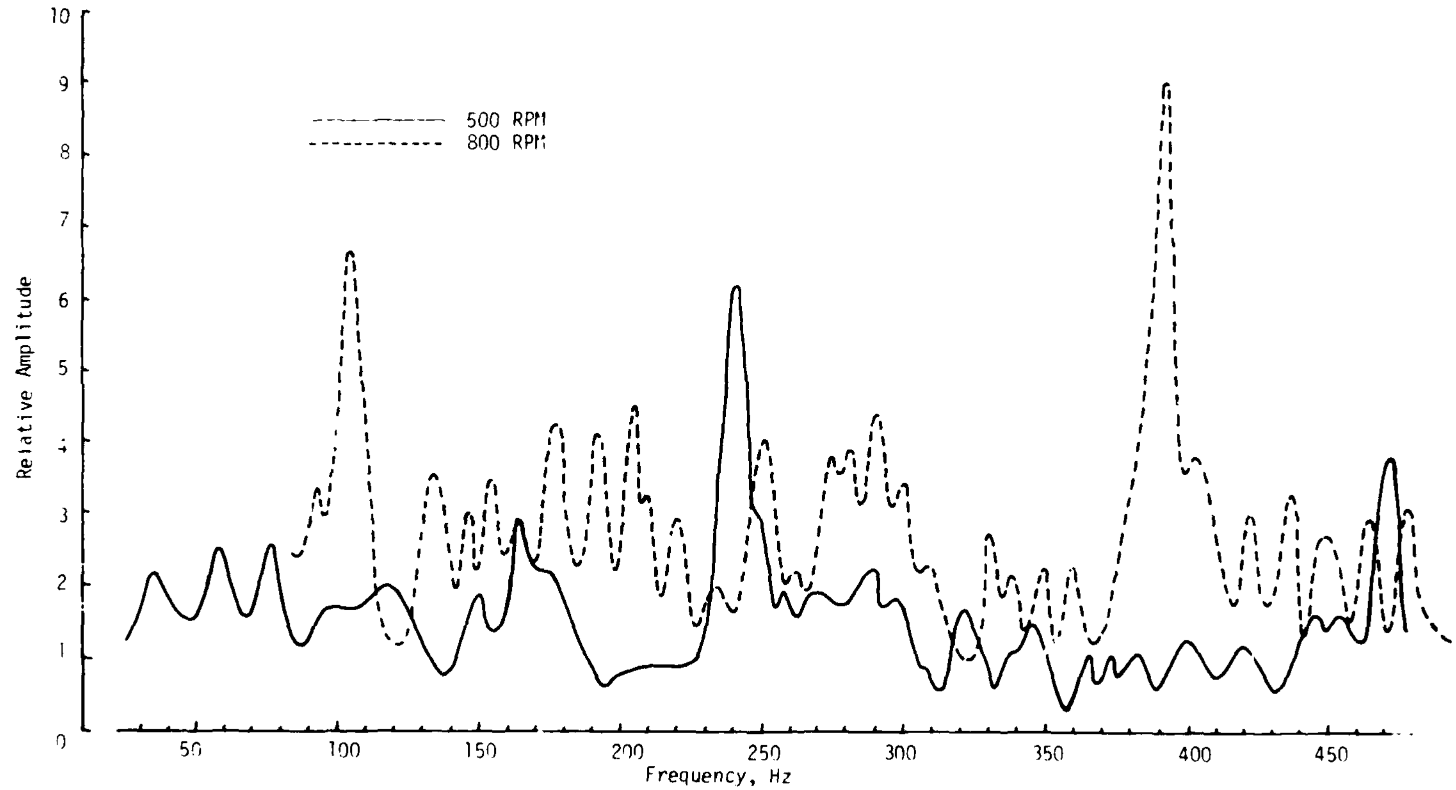


FIGURE 5.20 - HARMONIC DATA FOR USCGC COURAGEOUS, NO. 2 (PORT) ENGINE UNDER NO-LOAD OPERATION

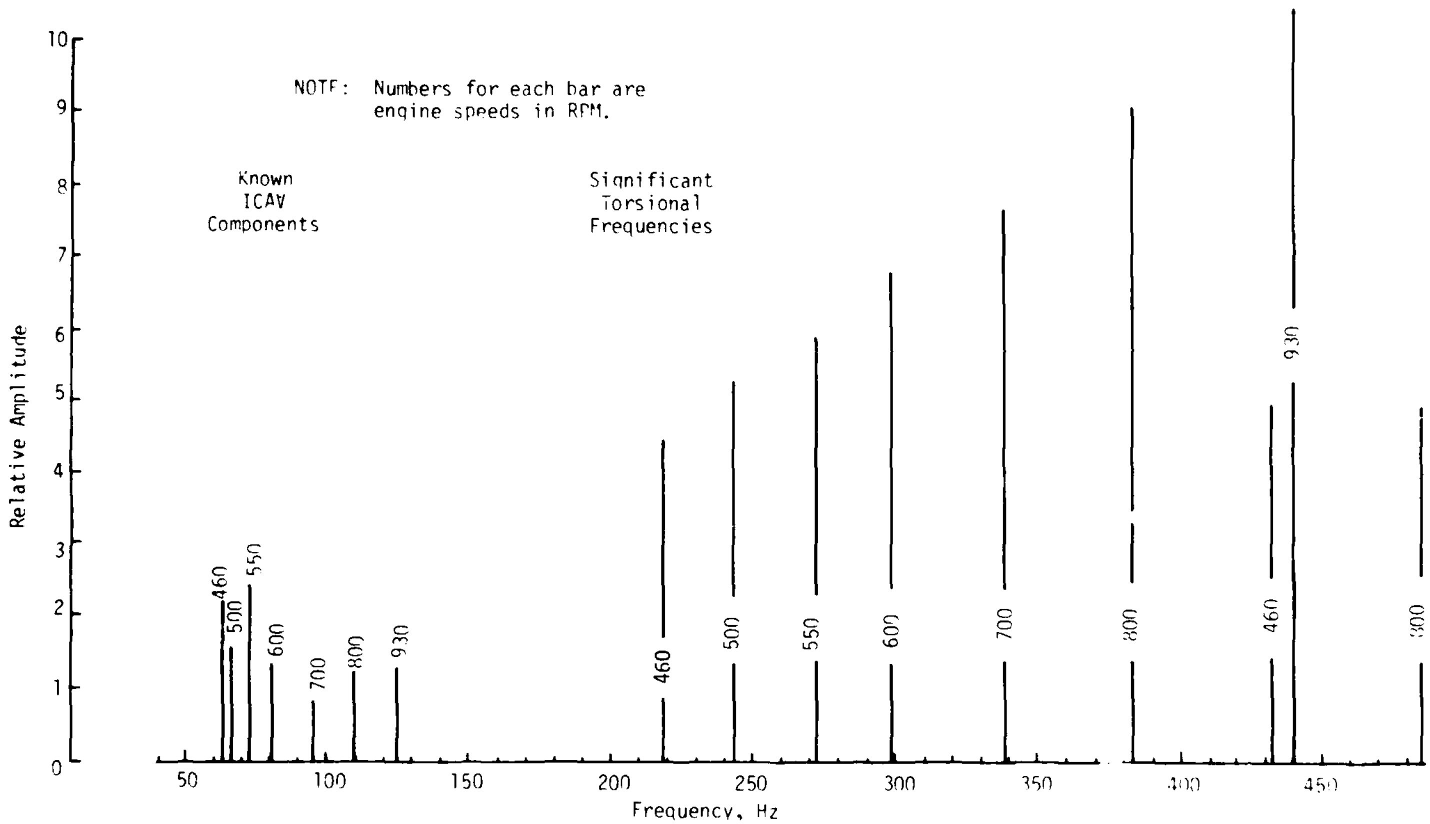


FIGURE 5.21 - SPECTRUM OF SIGNIFICANT TORSIONAL FREQUENCIES

related to each other in a ratio of about two-to-one, but not to the eighth-order driving frequency (the ICAV component of diagnostic significance). At low engine speeds there appears to be a ratio of four-to-eight to the eighth-order component, but this quickly disappears at higher engine speeds. The most significant feature displayed here is the direct proportionality of these high-order harmonics in both frequency and amplitude to engine speed. This is, of course, of no diagnostic value and in fact is the very feature of the torsional harmonic characteristics of large engine crankshafts that serves to complicate diagnosis of cylinder power imbalance by direct observation of eighth-order ICAV variations.

5.8 Caterpillar Six-Cylinder, Four-Stroke Model 3306 Engine

5.8.1 Test Procedures

A ladder tape was installed and the optical scanner with the Mk II detector used to acquire ICAV data from this engine in the laboratory at SwRI. Data were observed real-time on an oscilloscope and also recorded on magnetic tape. The only defect readily applied to this engine (which was available for only a short time and could not be modified to any extent) was underfuel in a specified cylinder. This was done by slightly loosening the fuel line connections to the desired injector and leaking off a portion of the injector pump output. This procedure allows a rather limited underfuel condition (estimated at up to 20% reduction) to be introduced without disturbing the entire injection system; however, this method did produce readily apparent ICAV changes in the engine. PKD was not measured due to the very short length of this test sequence.

5.8.2 Data Analysis

Figure 5.22 shows real-time third-order ICAV signals as photographed from the oscilloscope screen for various conditions of fueling defect, engine speed, and engine load. All signals behaved as expected, and even with this simple experimental set-up it is apparent that they could be used to diagnose individual cylinder power imbalance in this engine. The third-order ICAV signals displayed represent the direct response of the crankshaft to the individual cylinder firing events. This direct relationship (which is the diagnostically useful one) holds from idle speed (725 RPM) up to about 1200 RPM at which point extra "humps" appear in the waveform, indicating the onset of some torsional resonance.

5.8.3 Conclusions

- The data confirm that ICAV is a feasible diagnostic technique for detecting power imbalance in small- and medium-size diesel engines of similar configuration to the Caterpillar.

- The ICAV diagnostic technique used here can be applied only to engines that operate at firing frequencies far below prominent crankshaft torsional frequencies unless more sophisticated data acquisition and processing methods are developed.

- FIRING ORDER 1-5-3-6-2-4
- SYNCH. ON #1 CYLINDER
- THIRD ORDER ICAV - 30% BP FILTER

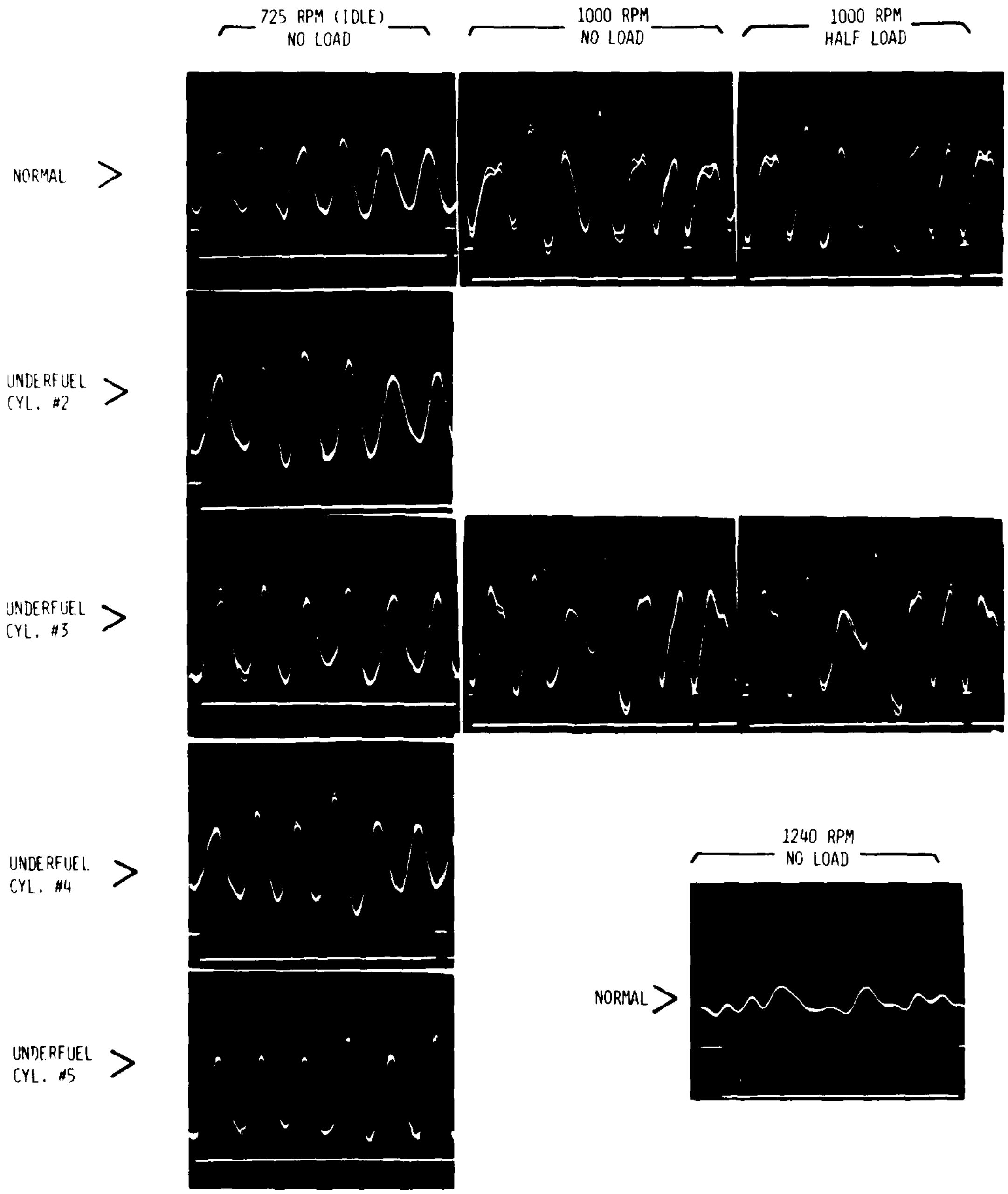


FIGURE 5.22 - ICAV TRACES FOR CATERPILLAR 3306 ENGINE

5.9 Cummins 12-Cylinder, Four-Stroke Model VTA 1710

5.9.1 Test Procedures

The test procedures followed on this engine were the same as described for the Caterpillar engine in Section 5.8, above. PKD was not measured.

5.9.2 Data Analysis

ICAV signals from the Cummins engine were inconclusive and are therefore not reproduced here. Six rather than twelve angular acceleration peaks were obtained on all ICAV signal records. No filtering or equipment adjustments could be found that produced an ICAV signal that even remotely resembled a normal waveform for a 12-cylinder engine. Time was not available for a thorough examination of all possible causes; therefore, this effort must be deferred to some future time when a test engine of this type is available for a long enough period so that a careful analysis of engine geometry, firing order, and so forth can be made to discover the cause for this anomalous behavior.

5.9.3 Conclusions

V12 engines of the Cummins type must be examined for ICAV indications as a separate entity. Satisfactory ICAV signals have been obtained in the past from V6 and V8 engines of two-stroke (Detroit Diesel) type, but evidently they are different from the four-stroke Cummins as regards ICAV changes resulting from induced power imbalances.

6. RECOMMENDATIONS

6.1 PKD

The questions to be answered here are fundamental and much like those that pertain to any future ICAV work with large diesel engines. First and foremost, we must precisely define the exact crankcase pressure changes that occur with specified leakage defects. The work effort required to do this is comparable to that needed for ICAV, and the same considerations apply. Some additional instrumentation and/or signal processing development could be required.

6.2 ICAV

The laboratory and field test work accomplished on large diesel engine diagnostics during the course of this project is well suited to serve as a basis for extrapolation of equipment and technique requirements to make ICAV a satisfactory means of realizing the objectives originally specified for this project. As explained previously in this report, the long crankshafts typical of large diesel engines result in operational engine speeds quite near the crankshafts' first torsional resonance, and this situation caused considerable difficulties in our attempt to achieve a viable diagnostic technique with ICAV. We can now outline in general terms the developmental steps which appear to be reasonable and prudent if work is to be continued toward the original goal.

As indicated previously, there are two requirements for further development of the ICAV diagnostic concept. The first is to improve the data acquisition technique itself. This involves designing and building more refined data acquisition equipment, which includes ladder tapes of greater precision, better means of installing these tapes, and more precise means of scanning and conditioning the raw ICAV data. Our field experience has demonstrated that the Mk II equipment design is quite close to being suitable for future work and, on balance, there appears to be no major defect in the Mk II electronics or the techniques employed for obtaining raw ICAV data.

The second requirement (and this will constitute the principal thrust of any future work) is for an effort directed toward developing advanced means for processing raw ICAV data to recover, in the most cost-effective means, those diagnostically significant changes in ICAV which are the result of cylinder power imbalance. In order to preserve a logical approach to this second task, we need to first carefully specify what we know and what we do not know about the ICAV technique as applied to large diesel engine diagnosis. This is done in the following paragraphs.

To begin with, in all cases (and this is of primary importance) we have observed an ICAV signal change any time a cylinder power imbalance has been induced into a large diesel engine as an artificial defect simulating

malfunction conditions which occur in the course of service (that is, injection system faults and so forth). We also know with certainty that these large engine ICAV changes are not of the simple nature expected from small diesel engines which have short, stiff crankshafts. It is apparent that the changes in ICAV which result from cylinder power imbalance in large diesel engines can only provide useful diagnostic information when successfully extracted from a very complex assortment of flywheel angular motions produced both by the effect we are seeking to monitor (the power input contribution of each individual cylinder firing event) and by various torsional resonances in the engine crankshaft assembly itself and, additionally, in the drive train consisting of gear box, propeller shaft, and propeller.

Any future efforts toward making ICAV a useful large diesel engine diagnostic tool should include as the first order of business the acquisition of the use of a suitable baseline engine whose mechanical condition is precisely known. With this engine we must record, analyze, and accurately define the various complex flywheel angular motions which are attributable to engine geometry alone. Lack of such a baseline engine was a primary difficulty during the course of the project just accomplished. The technique of choice for baseline ICAV analysis (and later for diagnosis in a hopefully simpler form) will proceed as follows: we monitor with our already proven means the ICAV excursions which occur during each cylinder firing sequence (two complete crankshaft rotations in the case of the four-stroke ALCO engines) and time-divide this complex analog waveform into sequential digitized samples of a number sufficient to assure that we can ultimately reconstitute analog waveforms which adequately display ICAV changes of diagnostic interest. When we sample the entire firing order of 16 cylinders and make the assumption that the waveform for each cylinder firing event will require 20 or more sample points in order to obtain a waveform definition precise enough for diagnosis, on the order of 320 to perhaps 1000 samples per firing order will be required. (The sample density needed is a function of the frequency bandwidth of the desired ICAV signal, and since this quantity is derived from the ICAV signal itself we cannot now exactly specify it.) Over a period of a few hundred crankshaft revolutions (the minimum requirement will depend on engine speed), we will accumulate time samples of the ICAV excursions produced during each complete set of cylinder firing events and store these in a logic system (i.e., a computer). The computer will average the data values for each sample slot individually, and from these averages we can put into memory storage sample values which can reconstitute an average ICAV waveform which is the mean of the entire number of complete sets of firing events recorded. This information can be read out, if desired, in the form of a CRT trace or as hard-copy on conventional chart recording equipment, and one may examine the ICAV variations for a complete firing order, averaged over many revolutions. These data are the normal engine or baseline ICAV information. We next introduce known engine defects (which can be quantified) and go through the same procedure.

After obtaining this second record and storing it in memory we now have in digital storage two conditions: a normal engine condition and a

defective engine condition. It is important to remember that this information is stored as an average value for each sample slot of the complete ICAV waveform. Each time sample slot (or "point") is processed individually. By means of suitable programming we can subtract the original (baseline) waveform information from the abnormal condition information point-by-point and derive a new set of values for each point. These data represent the effect on ICAV of the engine malfunction present during the second data run. This concept is straightforward, but by no means trivial to implement. For example, maintaining exact timing relationships such that each data point is taken at precisely the same angular place in the firing order is difficult, as are several other technical considerations such as processing strategy to reduce memory requirements. The prospect is still good, however, that after development the hardware itself may be of reasonable cost since the components of such a system are steadily declining in price, particularly with the rapid advance of techniques such as commercial digital high-fidelity sound recording.

There exists at the present time no means of implementing these proposed data acquisition and processing operations (subtraction of "bad" from "good") with simple analog hardware. That is to say, it is not possible, based on our experience during this project, to merely record the two ICAV waveforms and then to contrive by some means or other to subtract them with analog techniques. It appears that some variety of "computer processing" will be needed.

To briefly recap: we know that ICAV waveforms of an engine with cylinder power imbalance are <u>without exception</u> different from those of an engine that is functioning normally. Useful ICAV diagnostic information is there, but not available for use because it is buried within a confusion of overlapping flywheel motions caused by the effects of engine geometry (primarily the long crankshaft), firing order and, to a lesser extent, the load being driven by the engine. The best prospect for recovering this hidden information is as follows: engine ICAV data is acquired under normal conditions, no defects present. Later the procedure is repeated. At this later time, if no defects have developed, then subtraction of (more properly finding the difference between) the two data sets should produce an essentially flat trace. If, on the other hand, a defect is present, then the quantification of how much the second trace deviates from the first (and when we say "trace," we are talking about what is read point-by-point out of computer memory) is a measure of the deficiency in the engine's power imbalance. By means of a known test engine we determine what degree of deviation is significant and what is not, i.e., perform a calibration.

The preceding paragraphs have briefly outlined a general method by which ICAV can be made to function as a precise diagnostic tool for large diesel engines. Next we will consider some questions to be answered and then look at alternate (simpler and cheaper) data manipulation methods that might prove practical, depending on the answers we get to these questions.

The first question is whether, at a set of fixed engine speed/load conditions, the time-varying inputs to and outputs from the crankshaft

maintain constant phase relationships. We know the input combustion events' time frame, but there appears to be no simple means of determining with certainty whether the excursions of crankshaft angular velocity caused by the various torsional resonances are random in time or whether they are phase-locked to the cyclic power input applied by the cylinder firing events. We would say intuitively that the input/output events should be phase-locked, yet analysis of the ICAV hard-copy chart records which we have obtained during the course of the test work discloses what appears to be a significant amount of random phase change between the various waveform components. Every torsional order group is clearly not precisely the same as every other in the hard-copy chart record. If we observe the same ICAV traces in real-time on a monitor oscilloscope during engine operation, the waveforms appear remarkably steady to the eye; that is, it has very little apparent "jitter." The significance of this observation is that so long as the real-time waveforms stand still (with scope trace synchronization being applied at the same point in the firing order for each trace) the phase relationships of the ICAV components are fixed. The two presentations (hard-copy chart and scope trace) are, therefore, not in agreement. The eye has a remarkable ability to average repetitive motions such as traces across a scope face, and this effect leads us to ignore random excursions away from the average values observed in real time. We must conclude that real-time observations of ICAV should generally be considered suspect until verified by hard-copy transcriptions or other processed read-out that eliminates this effect.

We must determine with precision, as a first order of business in any future effort, exactly what constitutes normal flywheel angular motions of a test engine in good condition and the phase relationships of the ICAV components. If phase coherence among the crankshaft inputs and outputs proves to be acceptably good (and it turns out that we have been deceived in some way by our previous method of processing the chart traces), then ICAV data processing might be greatly simplified. Let us assume that the ICAV components do indeed stay phase-locked. We may then speculate on two somewhat simpler types of data processing equipment.

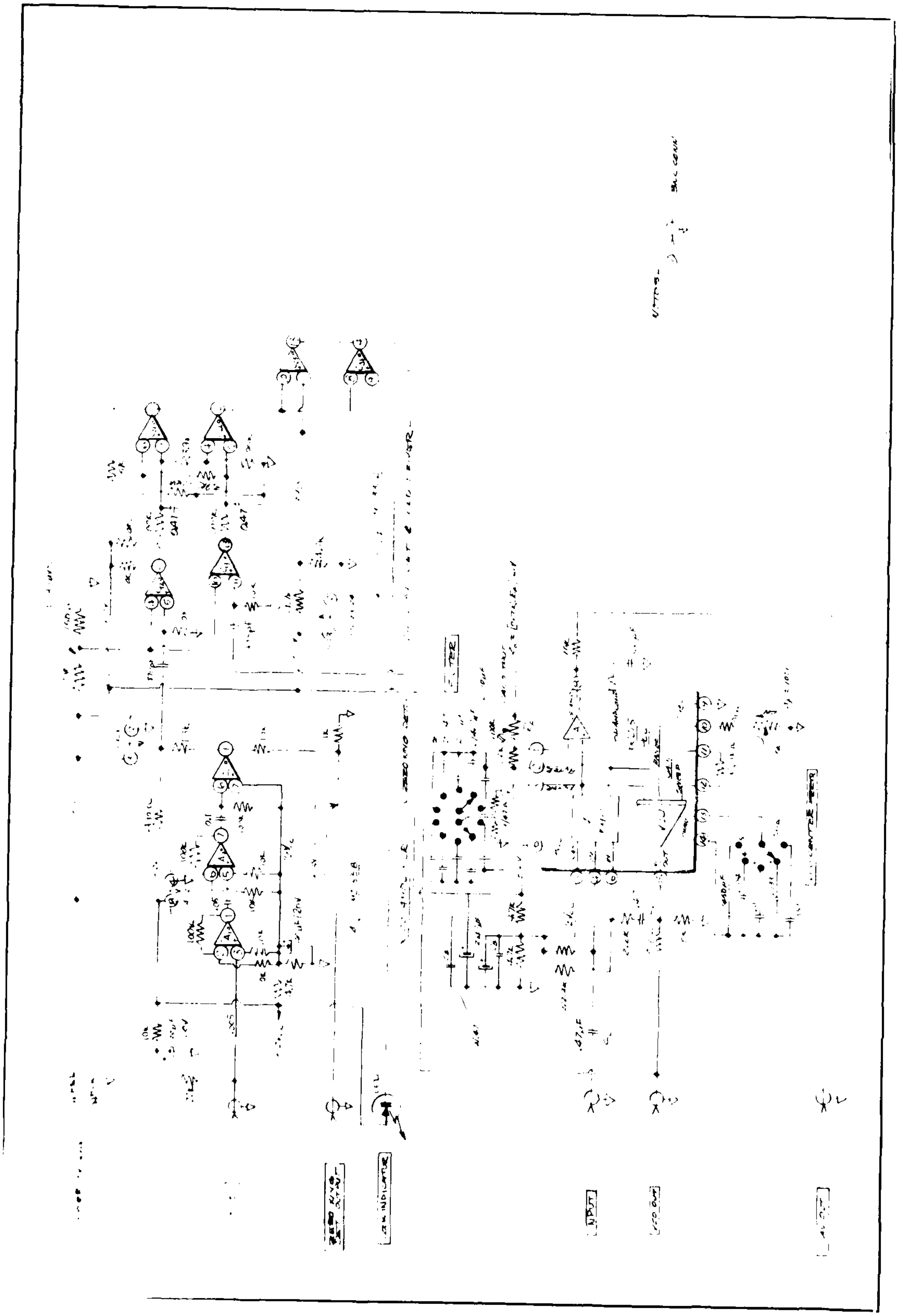
A first possibility is that it may be feasible to simply subtract, by analog means, the torsional resonance component of the ICAV waveform attributable to the crankshaft alone. (This is quite different from analog subtraction of the overall ICAV waveforms.) If this can be done, the ICAV signal remaining after such subtraction might be adequate for diagnostic purposes. We know that the principal cause of distortion in the ICAV trace of these large engines (as opposed to the smaller, short-crankshaft engines) is attributable to the first torsional resonance of the crankshaft assembly. To continue this line of reasoning: if such a method proves practical, then we may say that the possibility still exists (albeit a small one) for building a cheap and simple ICAV diagnostic system that is primarily analog in nature and does not involve digital memory and microprocessor functions. The question here is whether or not ICAV signals derived by these means can be made adequate for diagnostic purposes. These possibilities can be easily examined as part of any continuing effort at

relatively small cost. We must not lose sight of the fact that our objective is to cost-effectively diagnose large diesel engines, which are extremely difficult to diagnose by any means.

An alternate simplified approach may be possible with a scheme where we sample some part, probably the middle portion, of each firing event and then compute average values for these samples in their ''raw'' state; that is, while they contain both the desired ICAV information and effects produced by the various torsional resonances. By analyzing and quantifying patterns of changes in these sample amplitudes (only their average values) as a defect is introduced purposely, we may be able to effect satisfactory diagnosis with a very small number (one per cylinder) of samples rather than many, as outlined earlier.

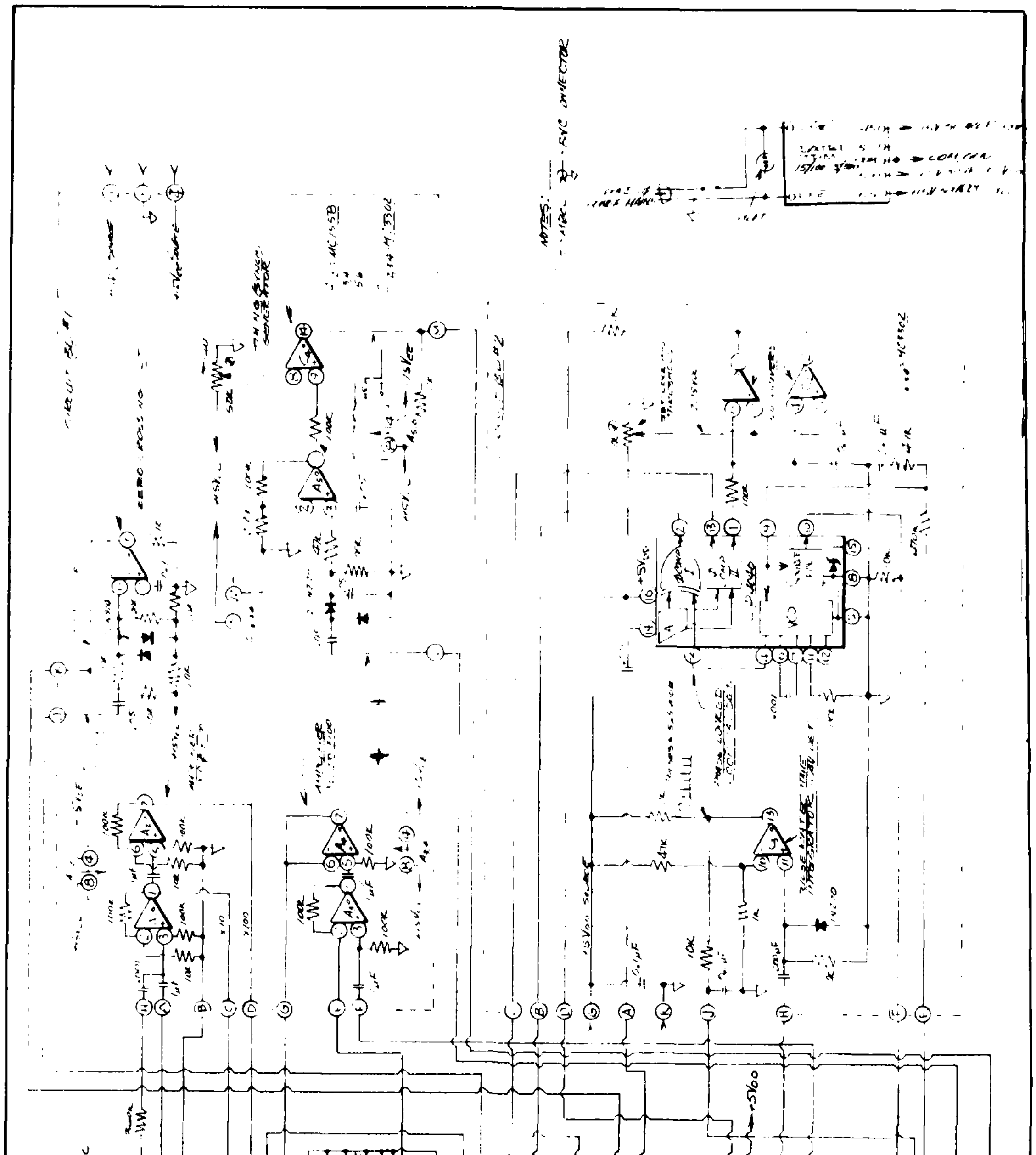
To sum up: first, we must produce the most cost-effective, straightforward, and accurate raw ICAV data acquisition system that we can. There appears to be no particular problem here. The results obtained by this effort are then applied to a satisfactory baseline engine of known characteristics to determine the direction which more sophisticated data processing must take. The most complex system, and the one which has the greatest assurance of operating satisfactorily, is a multiple-sampling microprocessor-based system which first processes each time sample and then stores it for later comparison point-by-point with similar data taken with engine defects present. The simplest system at the other end of the equipment cost spectrum would be one which subtracts by analog means the contribution of crankshaft torsional resonances and presents data in much the same manner of the experiments which have already been done. Finally, we should evaluate a minimum sampling system which would probably fall about midway in cost (but not necessarily in performance) between these two extremes.

APPENDIX A
ICAV System Mark I Schematic Diagram



APPENDIX B

ICAV System Mark II Schematic Diagram



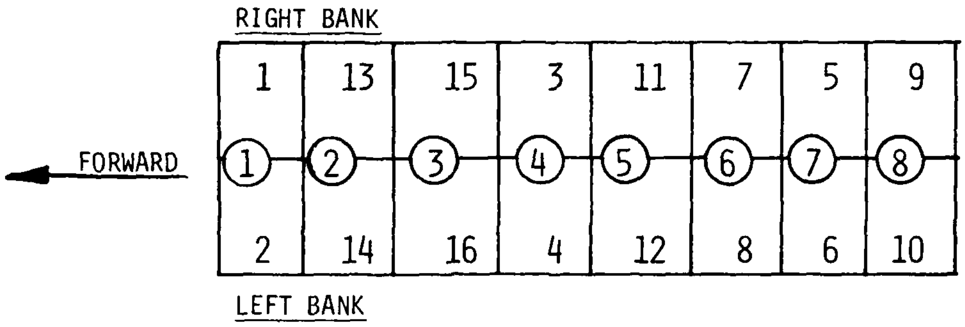
APPENDIX C

ALCO Engine Firing Orders (Standard and Reverse Rotation)

I. ALCO MODEL 251C-V16 STANDARD (LEFT HAND OR COUNTERCLOCKWISE) ROTATION

FIRING ORDER:

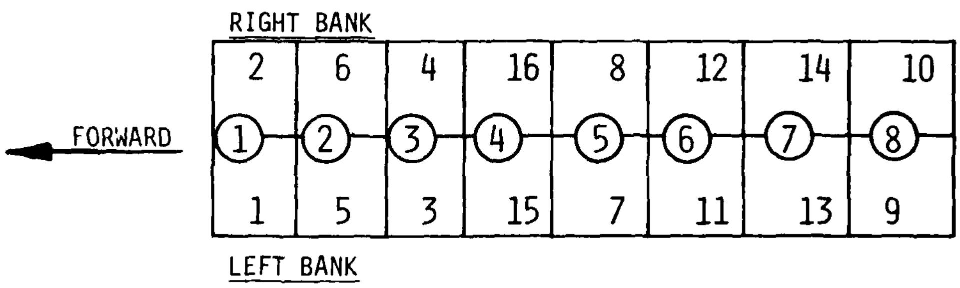
1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10 - 11 - 12 - 13 - 14 - 15 - 16
1R -1L -4L -4R -7R -7L -6R -6L -8R - 8L - 5R - 5L - 2R- 2L - 3R - 3L



II. ALCO MODEL 251C-V16 OPPOSITE (RIGHT HAND OR CLOCKWISE) ROTATION

FIRING ORDER:

1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10 - 11 - 12 - 13 - 14 - 15 - 16
1L -1R -3L -3R -2L -2R -5L -5R -8L - 8R - 6L - 6R - 7L - 7R - 4L - 4R



APPENDIX D

Wide-Band ICAV Frequency Spectra from Tests Onboard USCGC COURAGEOUS

This sheet replaces the 22 graphs of Appendix D. These graphs are chart recordings of not reproducible quality. However, copies will be made available to those interested recipients who request them from the Southwest Research Institute.

APPENDIX E
Report of New Technology

New technology has been developed under the scope of this contract, i.e., the system to detect Instantaneous Crankshaft Angular Velocity (ICAV) diagnostic information. Paragraphs 4.5.1 and 4.5.2 of this report present this system in some detail. A patent has been applied for, and is pending, on this new technology.

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